US009118216B2

(12) **United States Patent**
Corum

(10) **Patent No.: US 9,118,216 B2**
(45) **Date of Patent: Aug. 25, 2015**

(54) **PARAMETRIC POWER MULTIPLICATION**

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(73) Assignee: **CPG Technologies, LLC**, Newbury, OH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 2123 days.

(21) Appl. No.: **11/670,620**

(22) Filed: **Feb. 2, 2007**

(65) **Prior Publication Data**

US 2007/0132489 A1 Jun. 14, 2007

Related U.S. Application Data

(63) Continuation-in-part of application No. 11/069,476, filed on Mar. 1, 2005, which is a continuation-in-part of application No. 11/062,035, filed on Feb. 18, 2005, now abandoned, application No. 11/670,620, which is a continuation-in-part of application No. 11/069,682, filed on Mar. 1, 2005, which is a continuation-in-part of application No. 11/062,179, filed on Feb. 18, 2005, now abandoned.

(51) **Int. Cl.**

H01P 5/12	(2006.01)
H02J 17/00	(2006.01)
H02J 3/28	(2006.01)
H02J 15/00	(2006.01)
H01P 5/18	(2006.01)
H01P 5/22	(2006.01)

(52) **U.S. Cl.**
CPC . ***H02J 17/00*** (2013.01); ***H02J 3/28*** (2013.01); ***H02J 15/00*** (2013.01)

(58) **Field of Classification Search**
USPC 333/109, 116, 156, 161, 995, 128; 324/173–174, 207.2, 207.21, 207.25, 324/251, 252; 73/514.31, 514.39
See application file for complete search history.

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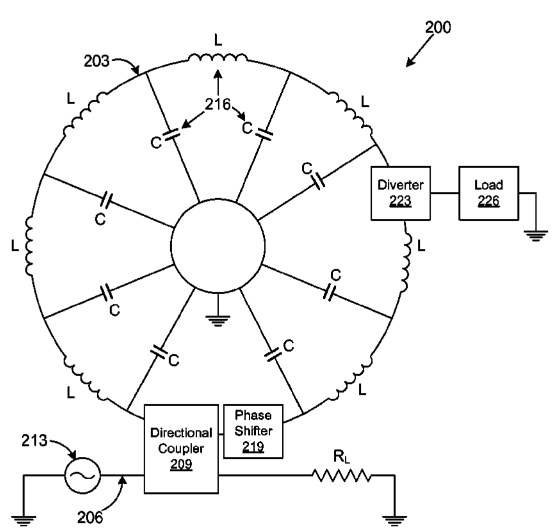
(57) **ABSTRACT**

In various embodiments, power multipliers and associated methods are provided that employ parametric excitation. In one embodiment, a ring power multiplier is provided that has a ring. A parametric reactance is associated with the ring that negates at least a portion of a physical resistance of the ring.

35 Claims, 14 Drawing Sheets



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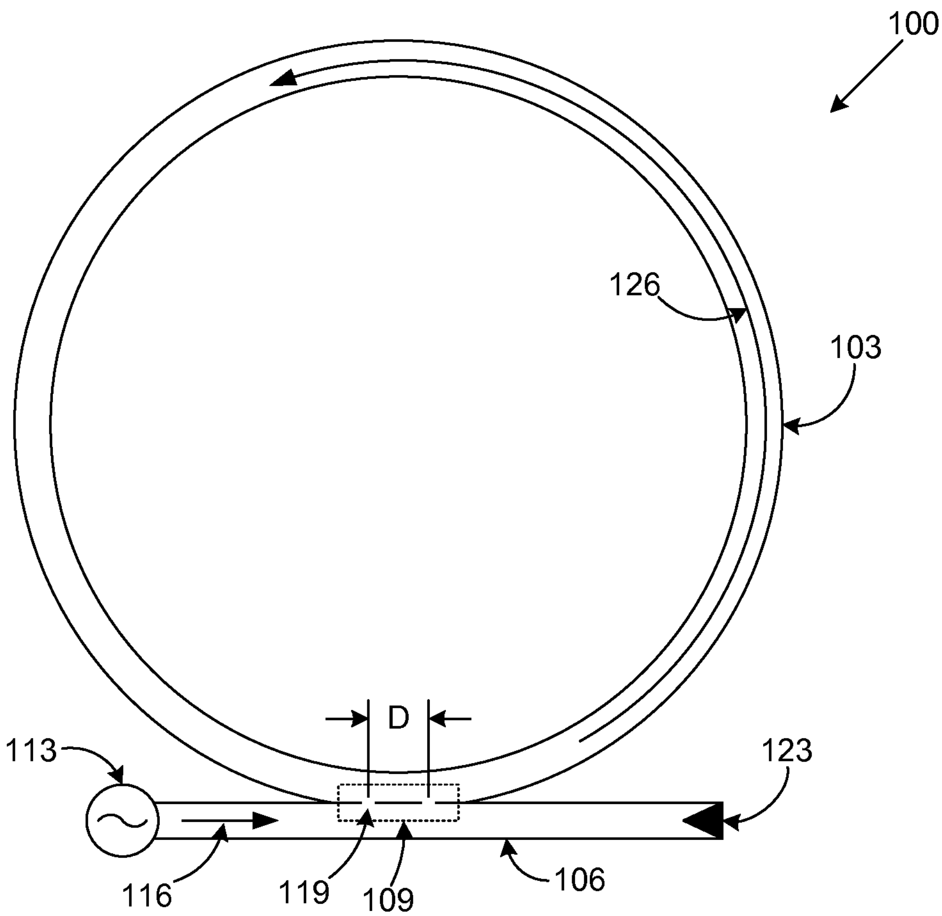


FIG. 1
(PRIOR ART)

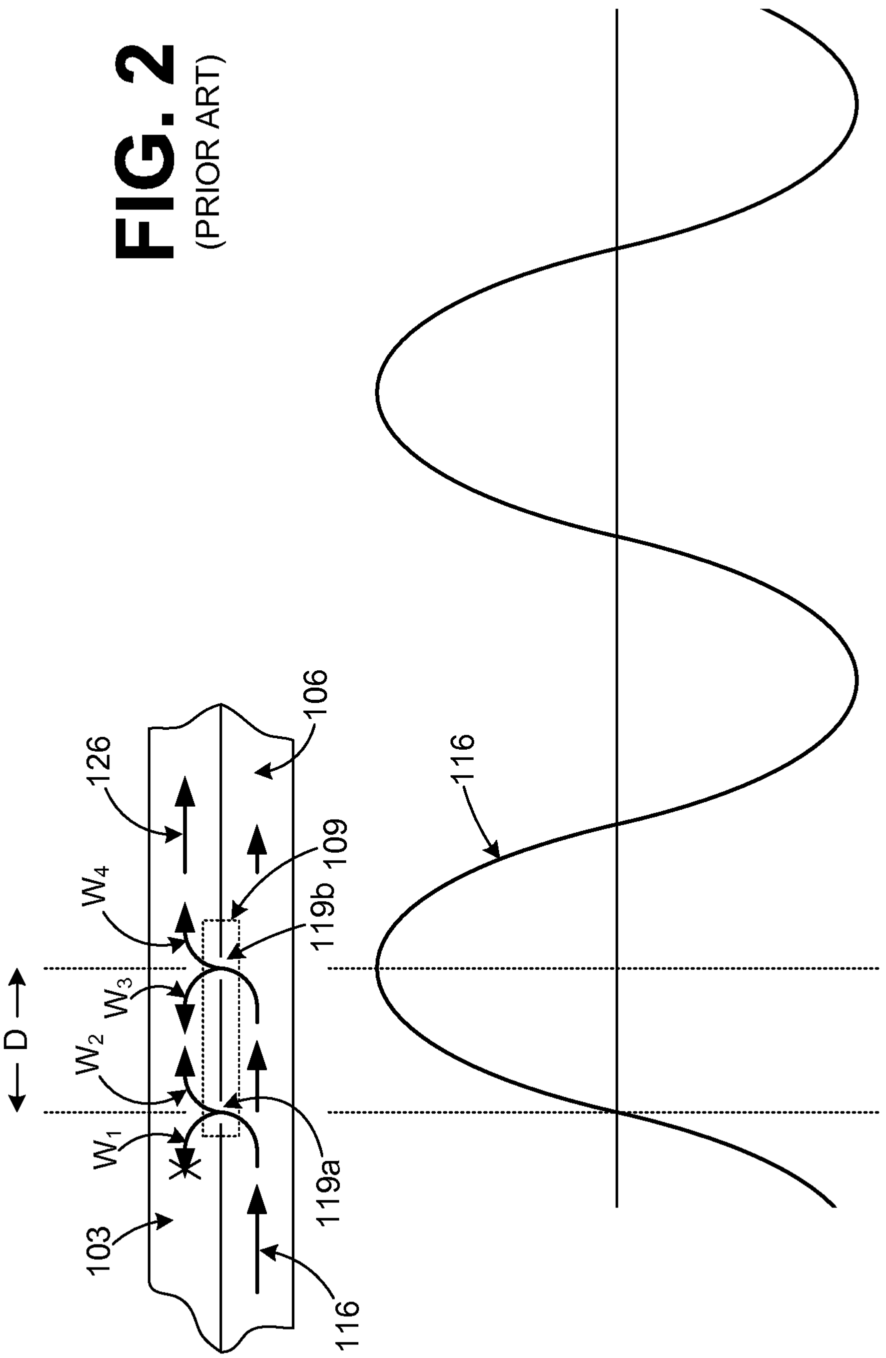


FIG. 2
(PRIOR ART)

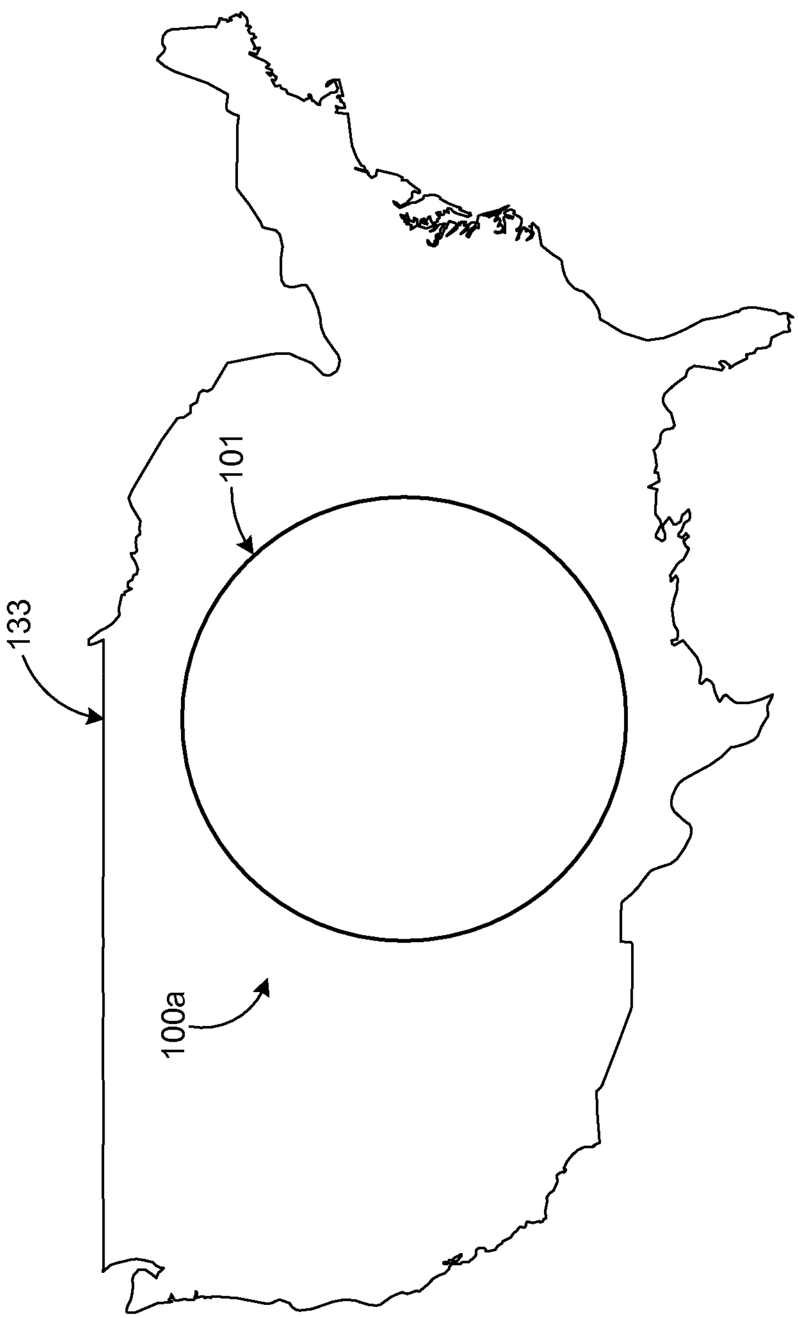


FIG. 3

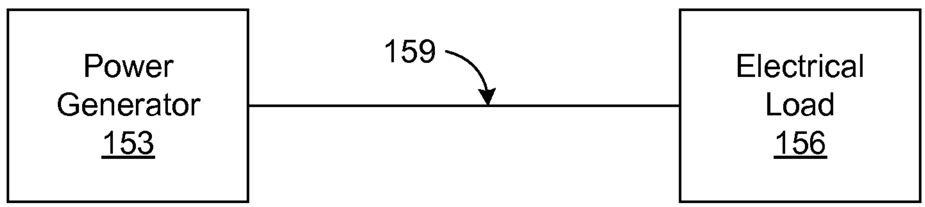


FIG. 4A

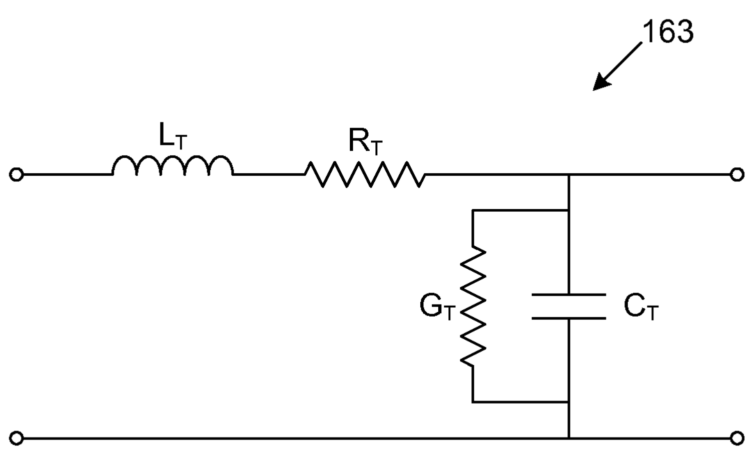


FIG. 4B

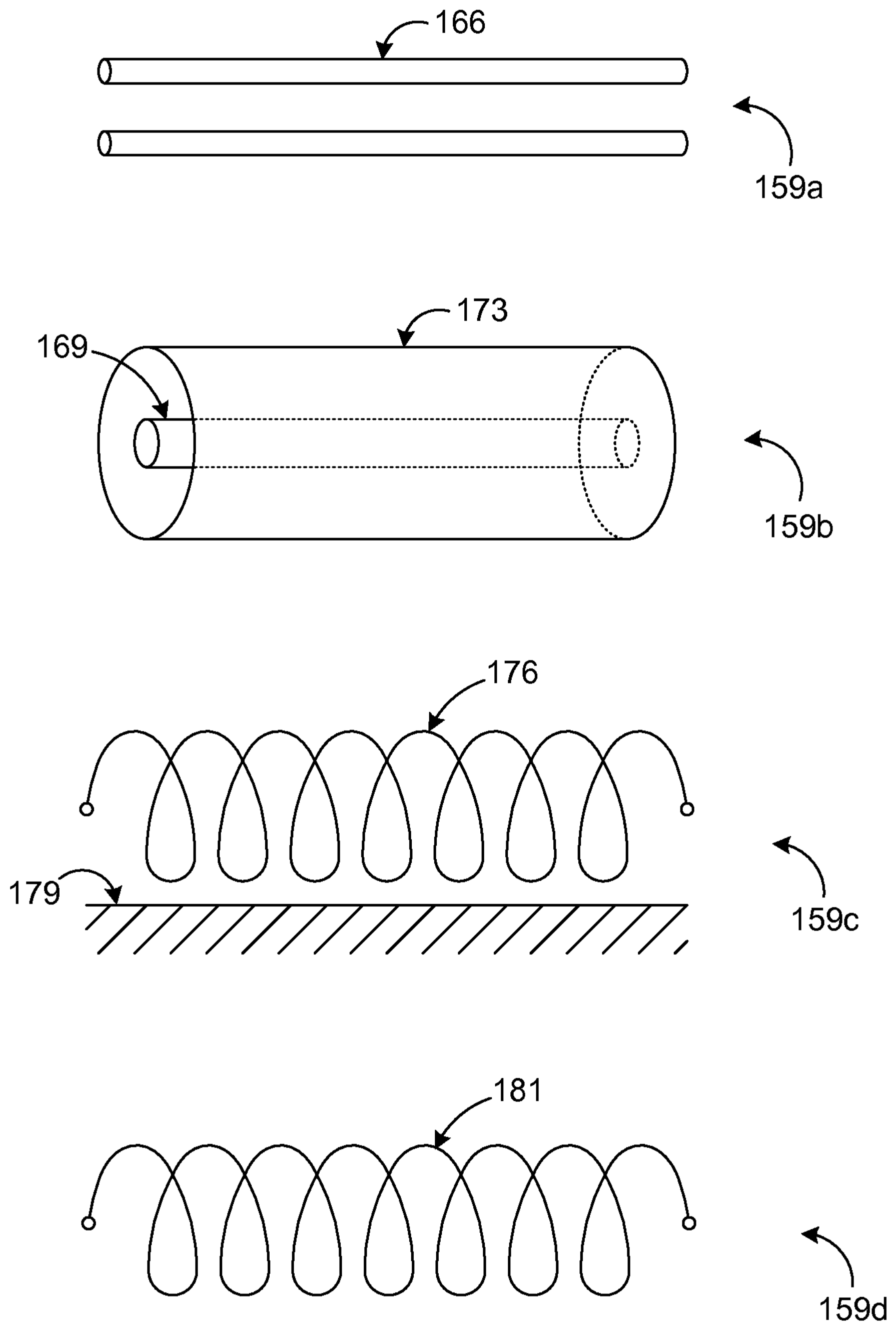


FIG. 5

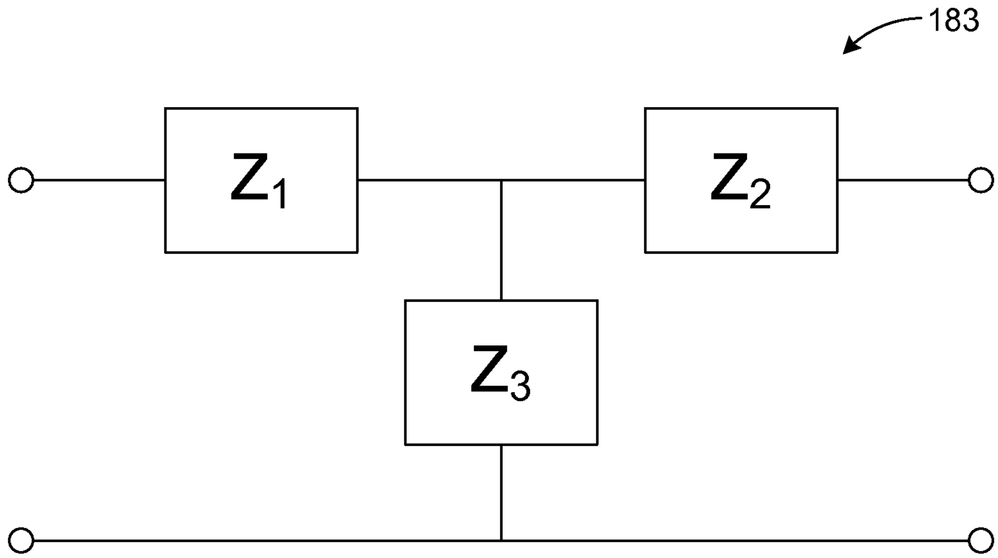


FIG. 6A

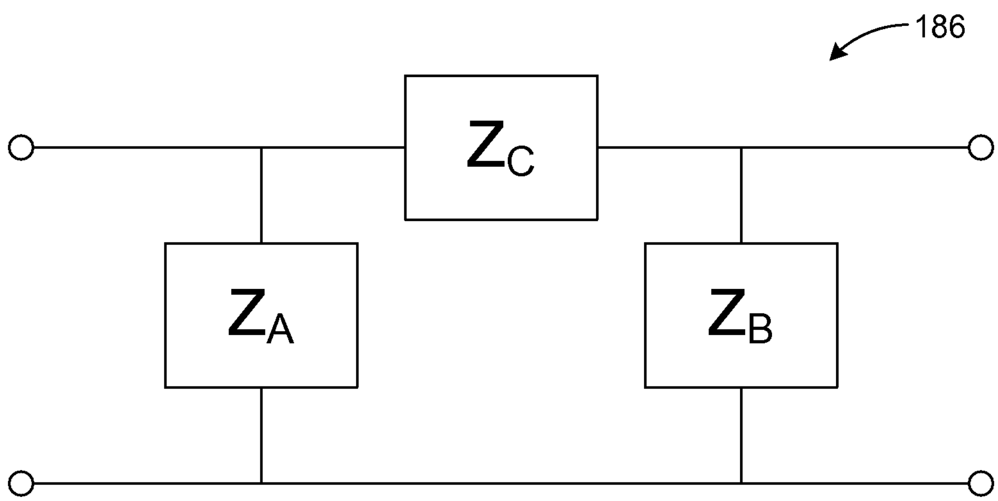


FIG. 6B

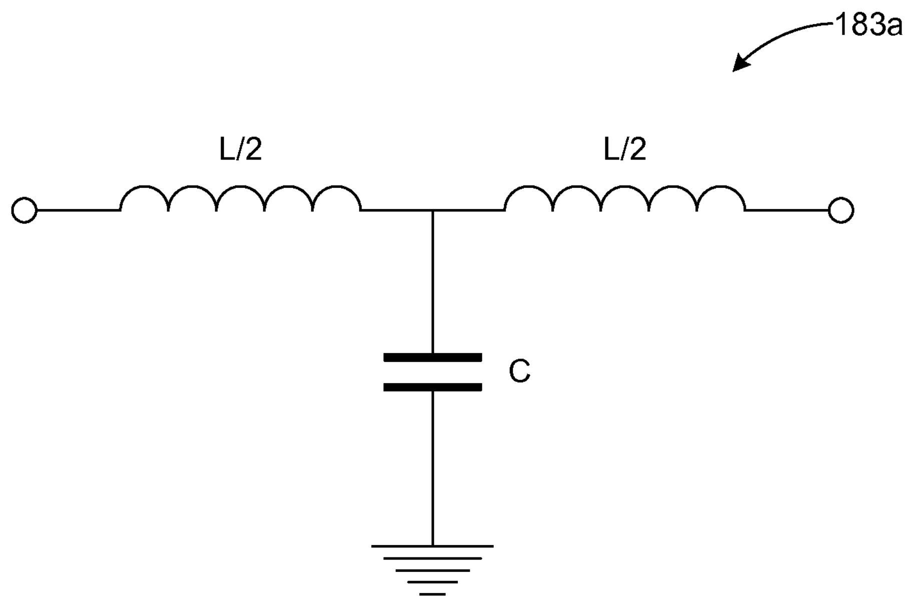


FIG. 7A

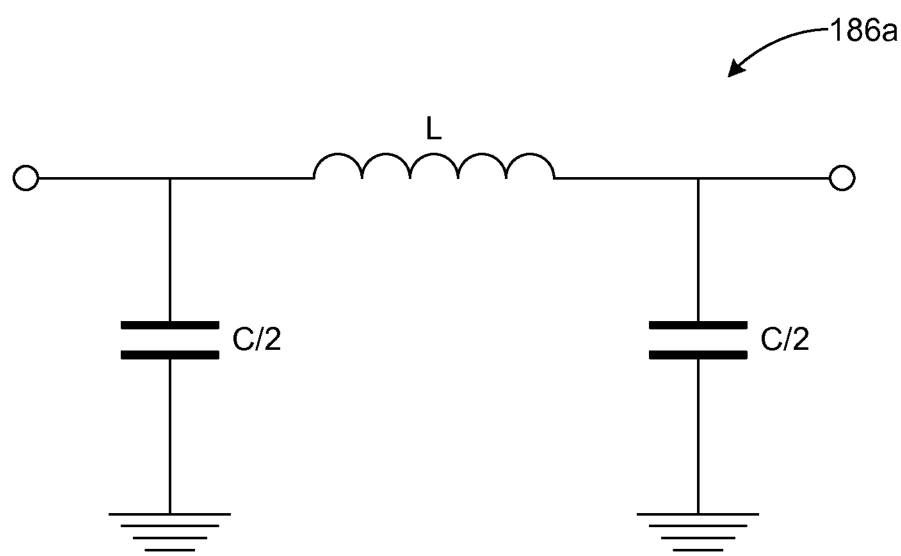


FIG. 7B

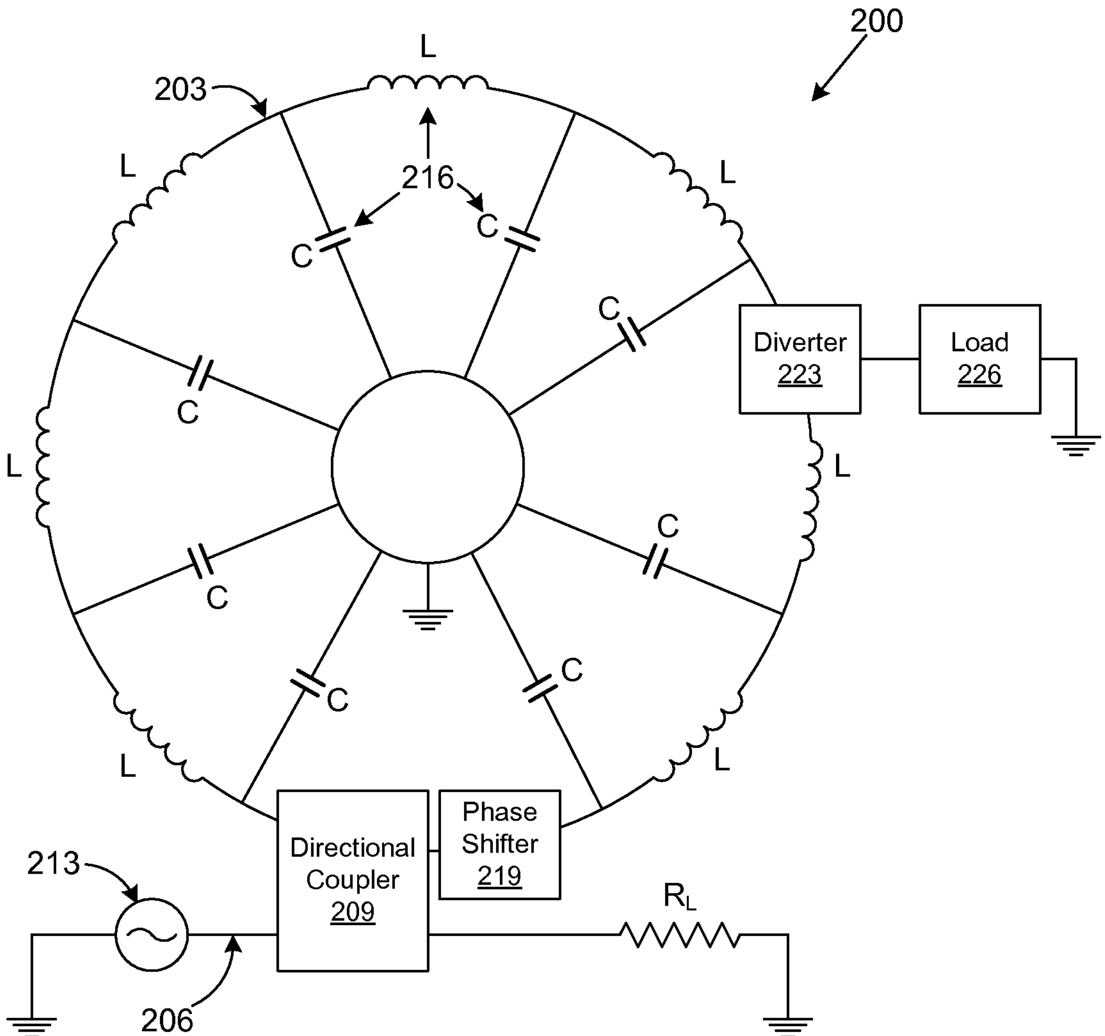
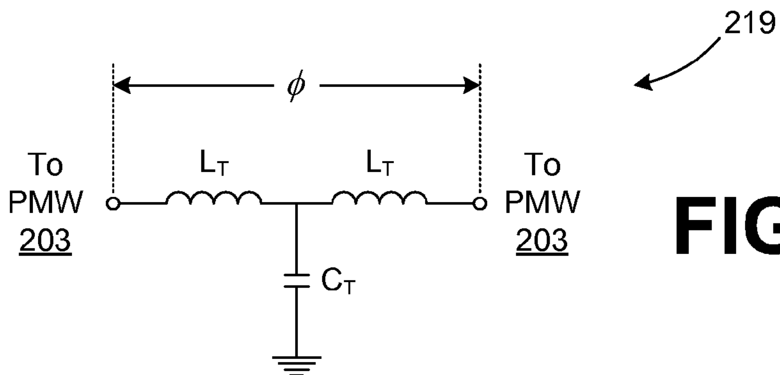
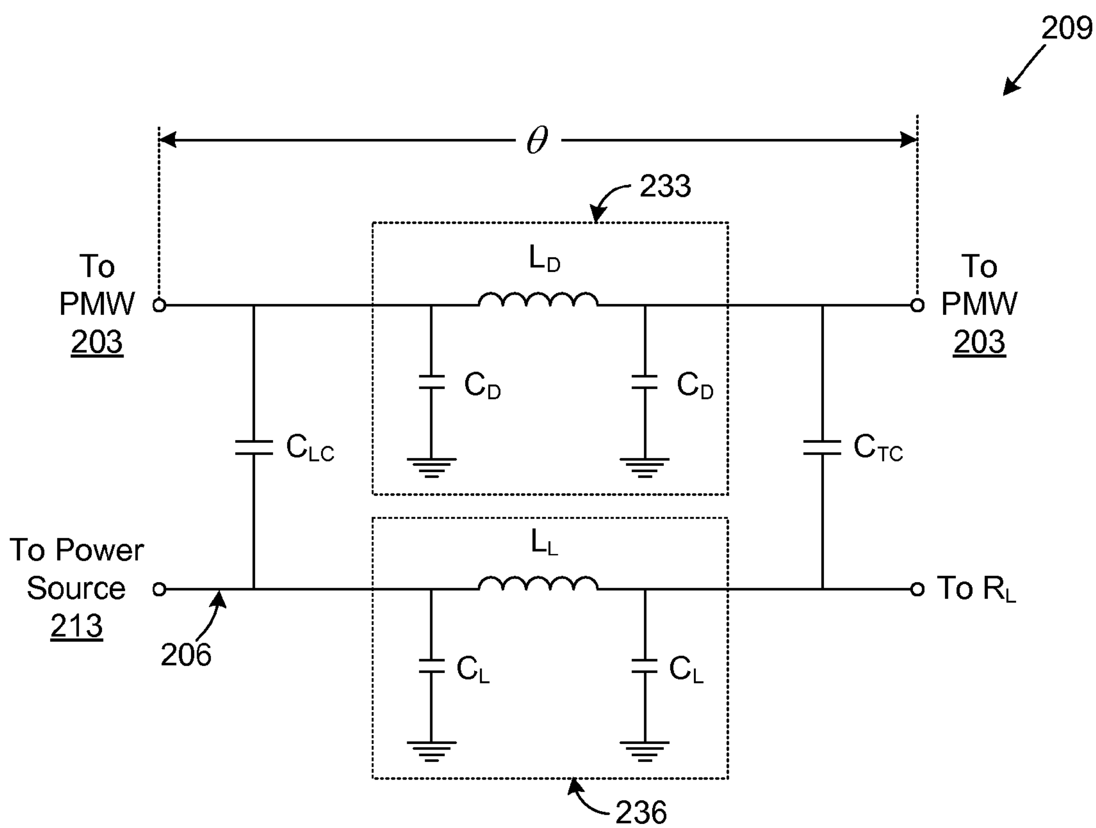

200
203
L
216
C
Diverter
223
Load
226
Directional
Coupler
209
Phase
Shifter
219
213
206
R_L

FIG. 8



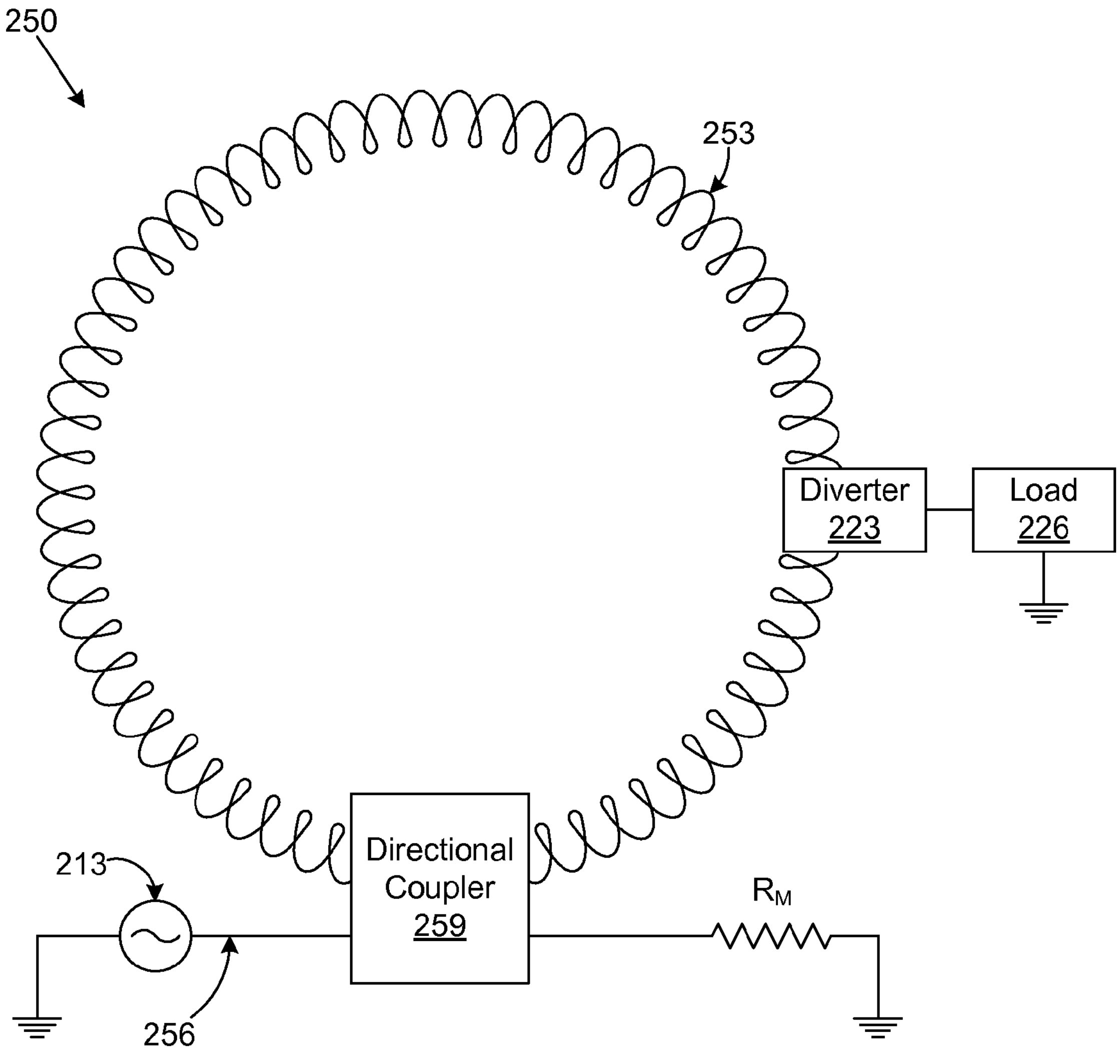
219
ϕ
To
PMW
203
L_T
L_T
To
PMW
203
C_T

FIG. 9



209
θ
233
To
PMW
203
L_D
To
PMW
203
C_D
C_D
C_{LC}
C_{TC}
To Power
Source
213
L_L
To R_L
206
C_L
C_L
236

FIG. 10



250
253
Diverter
223
Load
226
Directional
Coupler
259
213
256
R_M

FIG. 11

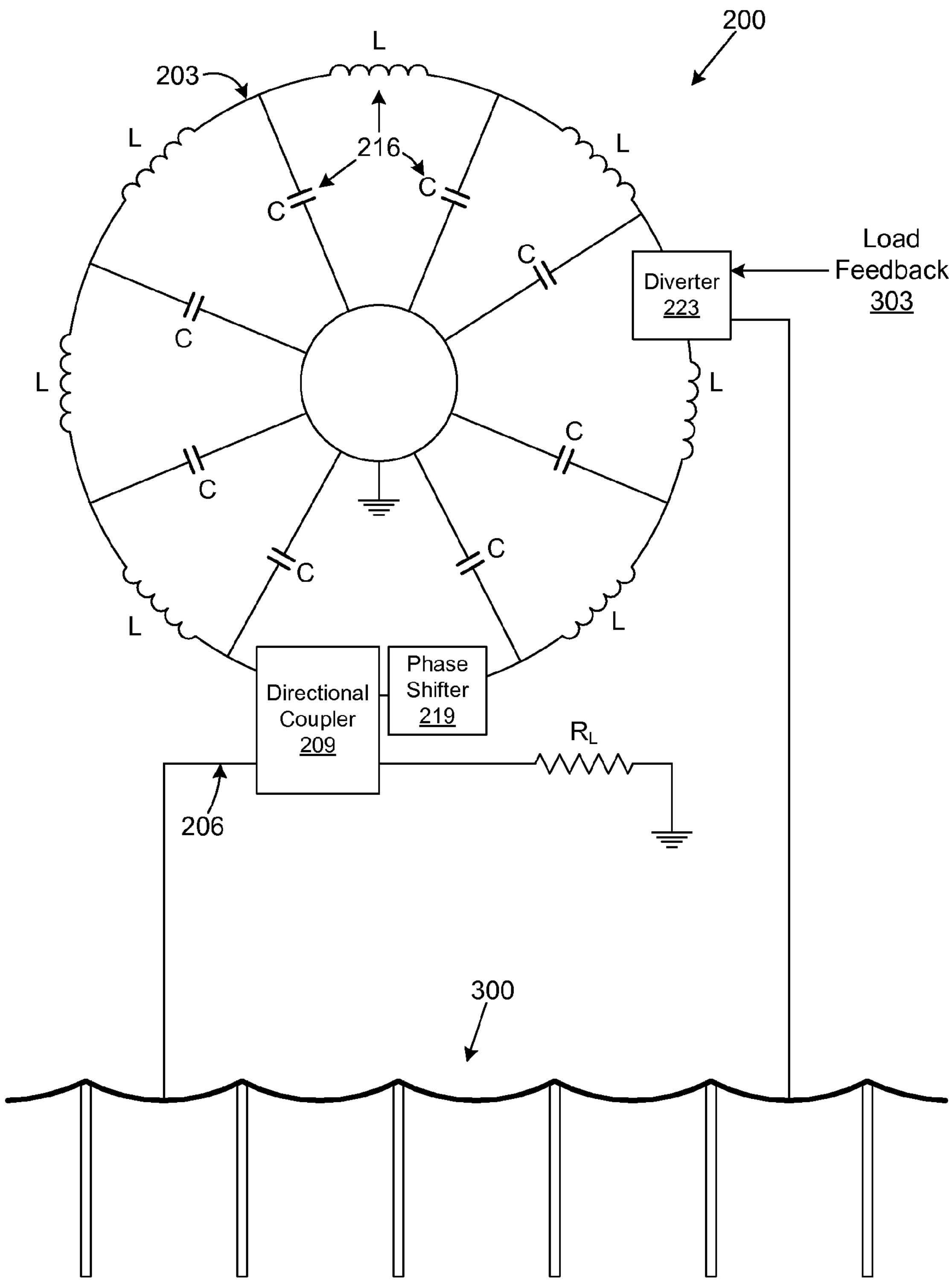
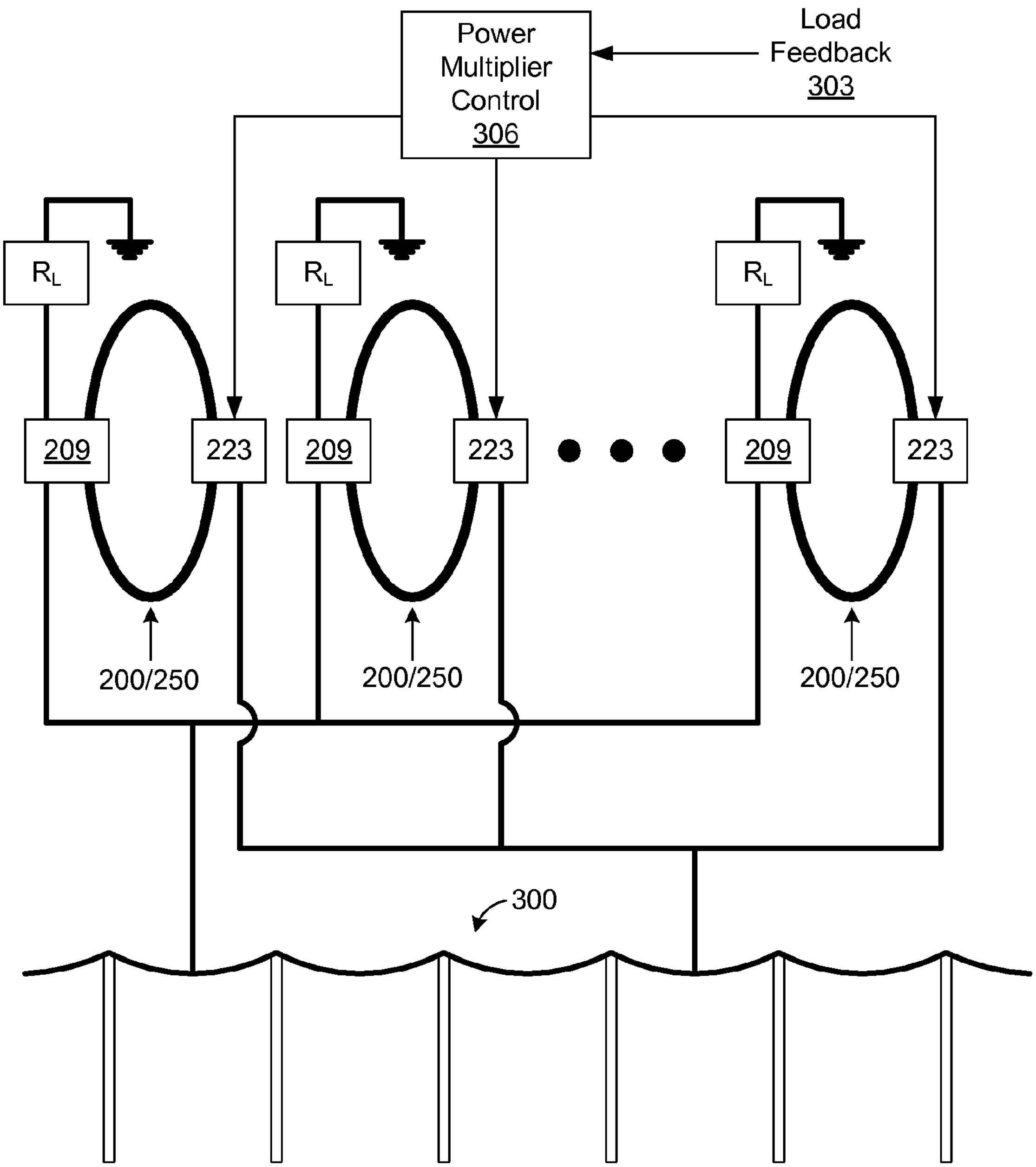
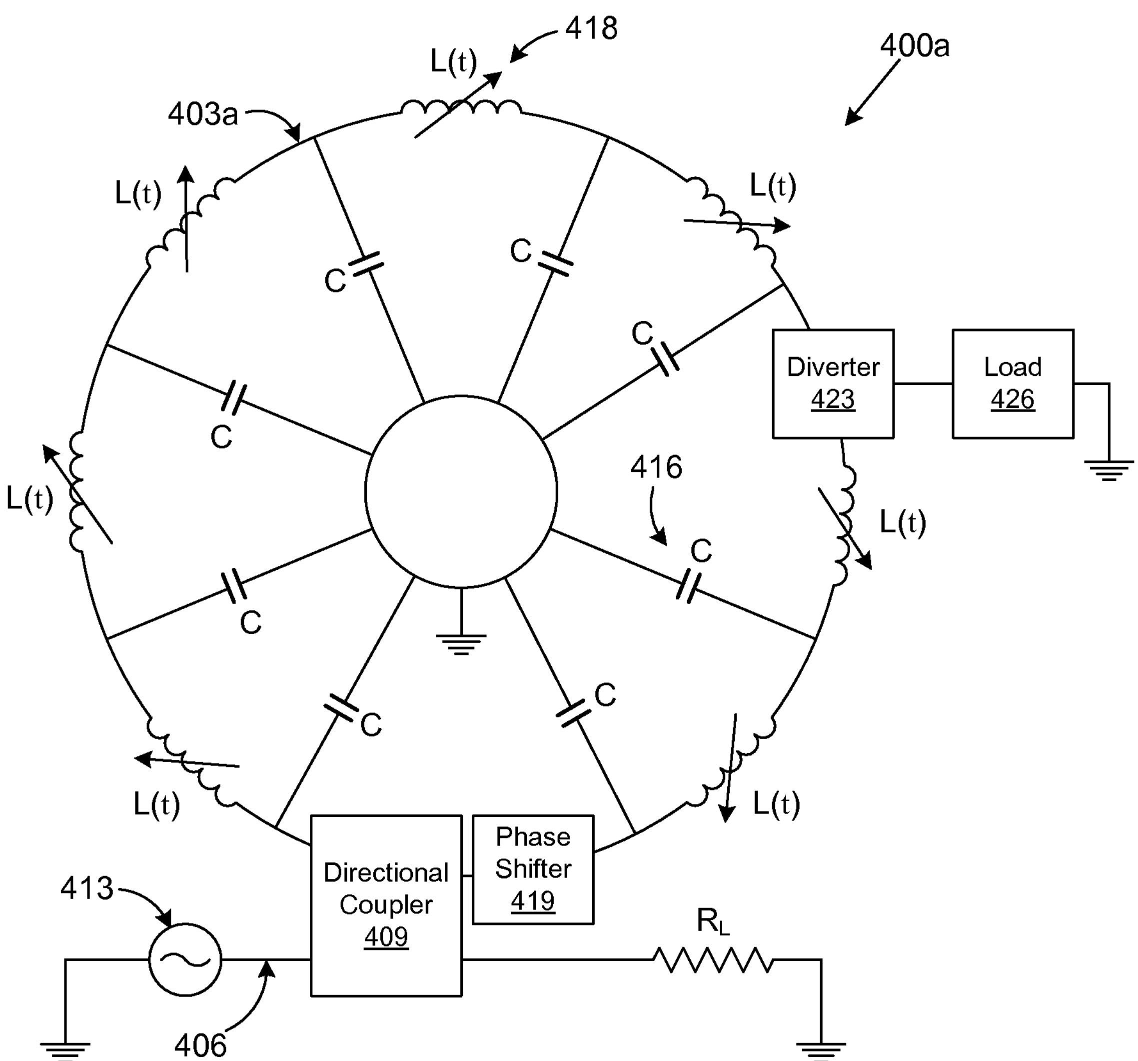

200
L
203
216
C
L
L
C
C
Load
Feedback
303
Diverter
223
C
L
L
C
C
C
C
C
L
L
Phase
Shifter
219
Directional
Coupler
209
R_L
206
300

FIG. 12



Power Multiplier Control 306
Load Feedback 303
RL
209
223
200/250
300

FIG. 13



418
L(t)
400a
403a
L(t)
L(t)
C
C
C
Diverter
423
Load
426
C
416
L(t)
L(t)
C
C
C
C
L(t)
L(t)
Directional
Coupler
409
Phase
Shifter
419
413
R_L
406

FIG. 14

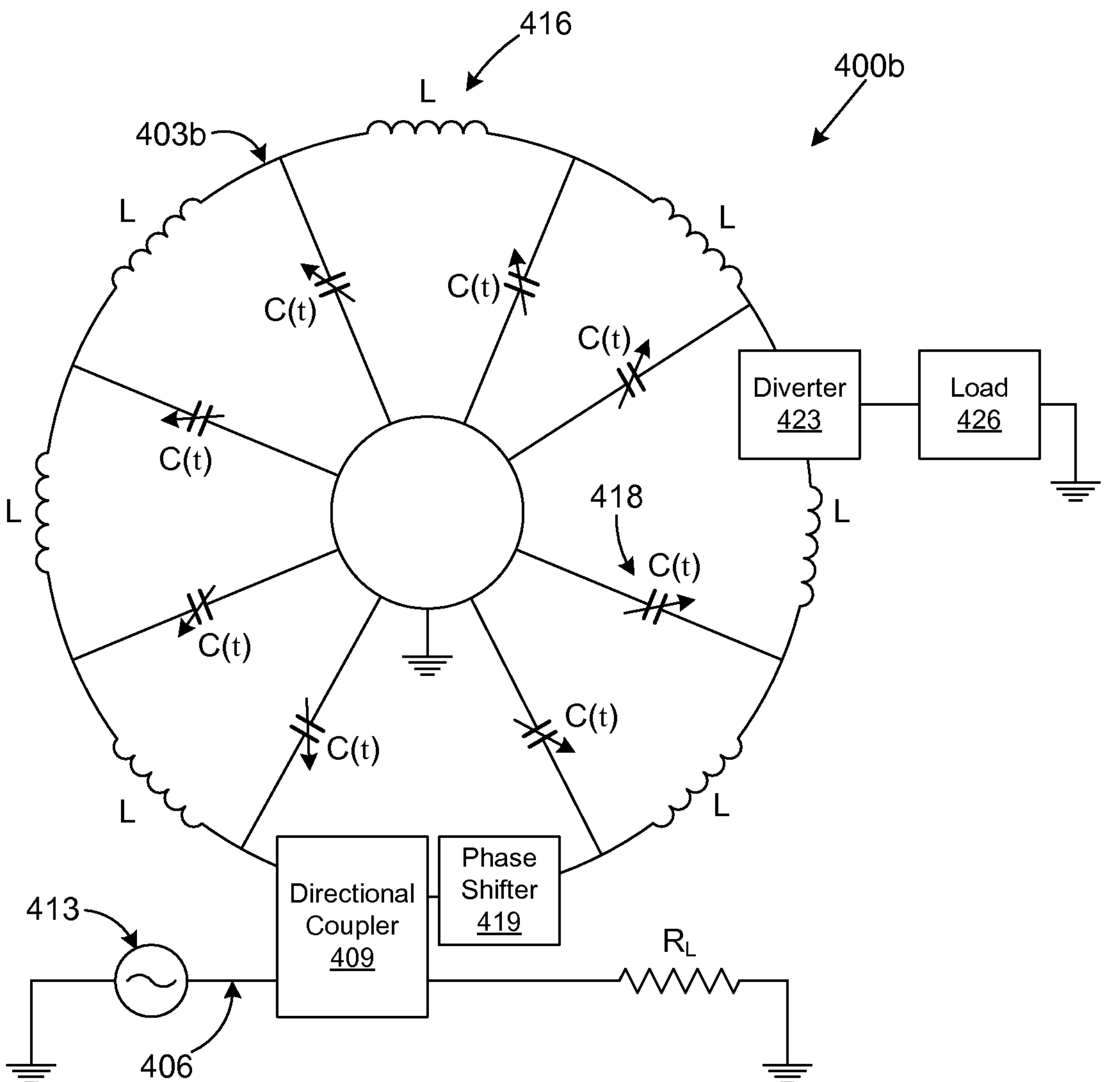

416
400b
L
403b
L
L
C(t)
C(t)
C(t)
Diverter
423
Load
426
C(t)
L
L
418
C(t)
C(t)
C(t)
C(t)
L
L
Directional
Coupler
409
Phase
Shifter
419
413
R_L
406

FIG. 15

PARAMETRIC POWER MULTIPLICATION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. Utility patent application Ser. No. 11/069,476 entitled, "ELECTRICAL POWER MULTIPLICATION," filed on Mar. 1, 2005 and issued as U.S. Pat. No. 8,638,182 on Jan. 28, 2014, which is a continuation-in-part of U.S. Utility patent application Ser. No. 11/062,035 entitled "ELECTRICAL POWER MULTIPLICATION" filed on Feb. 18, 2005, now abandoned, both of which are incorporated herein by reference in their entirety. This application is also a continuation-in-part of U.S. Utility patent application Ser. No. 11/069,682 entitled, "USE OF ELECTRICAL POWER MULTIPLICATION FOR POWER SMOOTHING IN POWER DISTRIBUTION," filed on Mar. 1, 2005 and issued as U.S. Pat. No. 8,629,734 on Jan. 14, 2014, which is continuation-in-part of U.S. Utility patent application Ser. No. 11/062,179 entitled "USE OF ELECTRICAL POWER MULTIPLICATION FOR POWER SMOOTHING IN POWER DISTRIBUTION" filed on Feb. 18, 2005, now abandoned, both of which are incorporated herein by reference in their entirety.

BACKGROUND

Power multiplication may be desirable for many applications that require significant power resources that cannot be economically or physically provided given the current state of power technology. For example, some have attempted to use conventional mechanical flywheel and capacitive storage arrangements for energy storage and power multiplication. However, such approaches are often inadequate due to the decay in amplitude and/or frequency of power output as stored energy is extracted or released.

Power multiplication may also be achieved electrically using an electromagnetic path configuration for accumulating electrical energy and stepping up or magnifying real AC power. Such technology has been taught by Tischer, F. J., *Resonance Properties of Ring Circuits*, IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-5, 1957, pp. 51-56. The power multiplier suggested by Tischer makes it possible to obtain practical power multiplication of 10 to 500 times the output power level of a given generator. The power multiplication is obtained without appreciable decay in either amplitude or frequency.

However, the power multiplier suggested by Tischer operates at relatively short wavelengths where the physical circumference of the device is on the order of an integral number of free space wavelengths given that the electrical length of the electromagnetic path suggested by Tischer equals an integer multiple of the wavelength of a traveling wave multiplied therein. At such short wavelengths, the physical size of the electromagnetic path is such that it can be practically constructed. However, power multiplication using an approach suggested by Tischer is not practical at lower power frequencies such as 60 Hertz with relatively long wavelengths as the size of the electromagnetic path would be on the order of several hundred miles. In addition, the maximum power that can be stored in the power multiplier suggested by Tischer is limited by the resistance of the waveguide.

In current electrical distribution systems such as the North American power grid it is often the case that Utilities experience severe mismatches between peak and average load demands. This can result in brown outs and blackouts in the system. Also, the North American power grid is being stretched to capacity. Consequently, it can be the case that brown outs and black outs may start chain reactions in the power grid that results in loss of reliable power.

In addition, another problem that energy markets face is that intervening load points such as cities often separate power generation stations from remote electrical loads. During heavy load times, the demand throughput cannot be conveyed from the power generation stations to the remote loads around the intermediate cities.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. **1** is a drawing of a power multiplier according to the prior art;

FIG. **2** is a drawing of a directional coupler of the power multiplier of FIG. **1**;

FIG. **3** is a drawing of an impractical power multiplier with respect to a geographical map illustrating a problem of practicing power multiplication using a power multiplier illustrated in FIG. **1** at power frequencies of relatively small wavelengths;

FIG. **4**A is a block diagram of power transmission line from a power generator to an electrical load;

FIG. **4**B is a schematic of an equivalent impedance per length of transmission line of FIG. **4**A;

FIG. **5** is a drawing of alternative transmission lines that might be employed as the power transmission line of FIG. **4**A and that have an equivalent impedance that can be modeled by the schematic of FIG. **4**B;

FIG. **6**A is a schematic of a T-network employed in a power multiplier according to an embodiment of the present invention;

FIG. **6**B is a schematic of a π-network employed in a power multiplier according to an embodiment of the present invention;

FIG. **7**A is a schematic of an embodiment of the T-network of FIG. **6**A;

FIG. **7**B is a schematic of an embodiment of the π-network of FIG. **6**B;

FIG. **8** is a schematic of a power multiplying network according to an embodiment of the present invention;

FIG. **9** is a schematic of a phase shifter employed in the power multiplier of FIG. **8** according to an embodiment of the present invention;

FIG. **10** is a schematic of a directional coupler employed in the power multiplier of FIG. **8** according to an embodiment of the present invention;

FIG. **11** is a schematic of a second power multiplier according to embodiment of the present invention;

FIG. **12** is a schematic diagram of a power multiplier coupled to a power distribution network according to an embodiment of the present invention;

FIG. **13** is a schematic diagram of multiple power multiplier coupled to a power distribution network according to an embodiment of the present invention;

FIG. **14** is schematic of a power multiplying network according to an embodiment of the present invention; and

FIG. **15** is a schematic of a power multiplying network according to an embodiment of the present invention.

DETAILED DESCRIPTION

With reference to FIG. **1**, shown is a power multiplier **100** according to the prior art. The power multiplier **100** includes a power multiplying waveguide **103** and a launching waveguide **106**. Both the power multiplying waveguide **103** and the launching waveguide **106** are conventional transmission lines such as hollow pipes, coaxial cables, parallel wire transmission lines. The launching waveguide **106** is coupled to the power multiplying waveguide **103** using a directional coupler **109**. An electromagnetic signal generator **113** is coupled to the launching waveguide **106** and generates an exciting traveling wave **116** that is launched into the launching waveguide **106**. The directional coupler **109** includes two slits **119** that are spaced apart by distance D. The distance D is approximately equal to ¼ of wavelength of the exciting traveling wave **116**. Thus, the electromagnetic signal generator **113** generates the exciting traveling wave **116** at a predefined frequency having a wavelength λ_W that is approximately four times the electrical distance D/λ_W. The launching waveguide **106** terminates in a matched load **123**. The total length of the power multiplying waveguide **103** is an integer multiple of the wavelength λ_W of the exciting traveling wave **116**. In the case that the power multiplying waveguide **103** is a closed circle or closed ring as shown, the total length of the power multiplying waveguide is equal to its circumference.

To operate the power multiplier **100**, the electromagnetic signal generator **113** generates the exciting traveling wave **116** that is launched in the launching waveguide **106**. When the exciting traveling wave **116** reaches the directional coupler **109**, a portion of the exciting traveling wave **116** is coupled into the power multiplying waveguide **103**, thereby creating a traveling wave **126** that propagates along the power multiplying waveguide **103**. The directional coupler **109** couples the portion of the exciting traveling wave **116** into the power multiplying waveguide **103** in such a manner that the traveling wave **116** travels in a single direction around the power multiplying waveguide **103**. Specifically, since the distance D between the slits **119** is approximately equal to ¼ of the wavelength λ_W of the exciting traveling wave **116**, all energy coupled into the power multiplying waveguide **103** propagates in a single direction as will be further described with reference to later figures.

In addition, since the length of the power multiplying waveguide **103** is an integer multiple of the wavelength λ_W of the exciting traveling wave **116**, the traveling wave **126** is spatially synchronized with the exciting traveling wave **116**. Under these conditions, the portion of the exciting traveling wave **116** that is continually coupled into the power multiplying waveguide **103** reinforces or is added to the traveling wave **126**. Consequently, the power of the traveling wave **126** may become quite large in magnitude. That is to say, the Poynting's vector power flow, ½Re{E×H*} is pumped up within the power multiplying waveguide, which is a linear, passive, distributed energy storage structure. The average energy of the traveling wave **126** is "distributed" in that it is evenly distributed throughout the entire length of the power multiplying waveguide **103**.

Once begun, the buildup of the power of the traveling wave **126** within the power multiplying waveguide **103** will continue until the losses around the power multiplying waveguide **103** plus the loss in the matched load **123** that terminates the launching waveguide **106** is equal to the power generated by the electromagnetic signal generator **113**. The power magnification M and optimum coupling C_{Opt} may be calculated as follows:

$$M = \frac{1}{(1 - A^2)}, \text{ and}$$

$$C_{Opt} = 1 - A^2,$$

where A is the field propagation decay for a single traversal of the power multiplying waveguide **103**. The quantity of C_{Opt} is that value of coupling for which the magnification is maximized.

The directional coupler has the property that energy leaking from the power multiplying waveguide **103** back into the launching waveguide **106** is reduced in magnitude. Also, energy leaking back into the launching waveguide **106** propagates only in a single direction towards the matched load **123** and, since such energy is of the correct phase, it cancels out the power propagating from the electromagnetic signal generator **113** to the matched load **123**. Consequently, when the exciting traveling wave **126** and the traveling wave **126** are in phase, the matched load **123** dissipates little or no power. Convenient nomograms for the engineering design of lossy power multipliers operating at ultra-high frequencies are described in Tomiyasu, K., "Attenuation in a Resonant Ring Circuit," *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-8, 1960, pp. 253-254.

Referring next to FIG. **2**, shown is a drawing of a portion of the power multiplying waveguide **103** and a portion of the launching waveguide **106**. Also shown is the directional coupler **109**. The drawing of FIG. **2** is provided to further explain the function of the directional coupler **109**. To explain the operation of the directional coupler **109**, the exciting traveling wave **116** is launched into the launching waveguide **106** and approaches the first slit **119***a*. A portion of the exciting traveling wave **116** enters the power multiplying waveguide **103** through the first slit **119***a* propagates in both directions within the power multiplying waveguide **103** as wave portion W_1 and wave portion W_2. The portion of the exciting traveling wave **116** that does not pass through the first slit **119***a* proceeds along the launching waveguide **106** until it reaches the second slit **119***b*. At this point, a second portion of the exciting traveling wave **116** enters the power multiplying waveguide **103** through the second slit **109***b* and propagates in both directions in the power multiplying waveguide **103** as wave portion W_3 and wave portion W_4. If the distance D between the slits is equal to ¼ of the wavelength λ_W of the exciting traveling wave **116** as shown, then the wave portion W_3 cancels out the wave portion W_1. Also, the wave portion W_2 reinforces the wave portion W_4, thereby resulting in the traveling wave **126**. As a consequence of the cancellation of wave portions W_1 and W_3, and the reinforcement of wave portions W_2 and W_4, the traveling wave **126** proceeds in a single direction around the power multiplying waveguide **126**. Given that the exciting traveling wave **116** and the traveling wave **126** are in phase or are spatially synchronized, the portion of the exciting traveling wave **116** that is coupled into the power multiplying waveguide **103** is continually added to the traveling wave **126**, thereby multiplying the power of the traveling wave **126**. The power of the traveling wave **126** is real power. This is to say that there is no reactive component.

Referring next to FIG. **3**, shown is a drawing of a map of the United States **133** that illustrates the problem that prevents the operation of power multipliers **100** at low frequencies such as power frequencies. Assume, for example, that the frequency of operation is 60 Hertz which represents the frequency of the power generation system of the United States. Assuming that the speed of light is approximately 300,000 km/sec, at 60 Hertz, the wavelength of both the exciting traveling wave **116** and the traveling wave **126** is calculated as:

$$\lambda_w = \frac{c}{f} \approx \frac{300{,}000 \text{ km/sec}}{60 \text{ Hz}} \approx 5000 \text{ km.}$$

Thus, the length or circumference of a hypothetical power multiplying waveguide **100*a*** would have to be approximately 5000 Kilometers. Consequently, a corresponding hypothetical transmission line **101** employed in the power multiplying waveguide **100*a*** would be approximately 5000 Kilometers in length. Obviously, due to the size involved, the creation of such a power multiplying waveguide **100*a*** is not physically practical and is cost prohibitive.

Turning then to FIG. **4**A, we turn our attention to a discussion of power transmission lines. In FIG. **4**A, a power generator **153** is electrically coupled to an electrical load **156** by a power transmission line **159**. Such a transmission line **159** may be traditionally employed, for example, to distribute power to homes and businesses as can be appreciated by those with ordinary skill in the art.

Referring next to FIG. **4**B, shown is an equivalent circuit **163** that illustrates the equivalent impedance per unit length of the transmission line **159** (FIG. **4**A). Specifically, each unit length of the transmission line **159** includes series inductance L_T and series resistance R_T. Also, between the conductors of the transmission line **159** are a shunt capacitance C_T and a shunt conductance G_T. Accordingly, the equivalent impedance per unit length of the transmission line **159** may be expressed in terms of a series inductance L_T, a series resistance R_T, a shunt capacitance C_T, and a shunt resistance R_T.

The equivalent circuit **163** reflects that fact that transmission lines **159** direct the propagation of field energy. The field energy propagating along a transmission line **159** is stored in the magnetic fields and electric fields associated with the structure of the transmission line **159** itself. On a mode-by-mode basis, one can equate the magnetic field energy stored in a transmission line **159** to the magnetic field energy stored in an equivalent distributed inductance. Also, the energy stored in the electric fields of the line can be equated to the energy stored in an equivalent distributed capacitance. Field power losses per unit length of the transmission line **159** can be equated to the equivalent series resistive and shunt conductive losses per unit length.

Turning then to FIG. **5**, shown are various embodiments of the transmission line **159** (FIG. **4**A) for which the equivalent impedance may be expressed using the equivalent circuit **163** (FIG. **4**B) discussed above. For example, transmission line **159** may comprise, for example, a parallel transmission line **159*a*** that includes parallel conductors **166**. Alternatively, the transmission line **159** may comprise a coaxial transmission line **159*b*** that includes an inner conductor **169** and an outer conductor **173**. In yet another alternative, the transmission line **159** may comprise an electrical structure **159*c*** that includes a conductor **176** of a predefined geometry situated with respect to a ground plane **179**. Alternatively, the conductor **176** may be situated with respect to a second such conductor rather than the ground plane **179**. The predefined geometry of the conductor **176** may be, for example, a helix or other geometry. In still another alternative, the transmission line **159** may comprise an electrical structure **159*d*** that comprises a single conductor **181** in the form a helix or other appropriate shape. In addition the transmission line **159** may comprise other types of transmission lines and electrical structures such as, for example, strip lines, fiber optic cables, and so on as can be appreciated by those with ordinary skill in the art.

Assuming that were actually possible to create the power multiplier **100*a*** at power frequencies such as 60 Hertz, such a power multiplier **100*a*** would involve the use of transmission wire in one of the configurations described above. In this respect, the impedance of such a transmission wire can be calculated and the equivalent impedance in terms of the series inductance L_T (FIG. **4**B), the series resistance R_T (FIG. **4**B), the shunt capacitance C_T (FIG. **4**B), and the shunt conductance G_T (FIG. **4**B) can be determined.

With reference to FIGS. **6**A and **6**B, shown are a T-network **183** and a π-network **186** that may be employed according to the various embodiments of the present invention. In this respect, the T-Network **183** includes series impedance Z_1 and series impedance Z_2. The T-Network **183** also includes parallel impedance Z_3. The characteristic impedance Z_0 of a symmetrical T-network **183** shown may be calculated as follows:

$$Z_0 = \sqrt{Z_1(Z_1 + 2Z_3)}.$$

The π-network **186** includes parallel impedances Z_A and Z_B. The π-network **186** also includes series or middle impedance Z_C. The characteristic impedance Z_0 of a symmetrical π-network **186** may be calculated as follows:

$$Z_0 = Z_A\sqrt{\frac{Z_C}{(Z_C + 2Z_A)}}.$$

For further discussion of both the T-network **183** and/or the π-network **186**, reference is made to Terman, F. E., *Radio Engineering Handbook*, McGraw-Hill, 1943, pp. 172-178, 191-215, which is incorporated herein by reference in its entirety. The T-network **183** and/or the π-network **186** may be employed, for example, in the construction of a power multiplier according to various embodiments of the present invention as will be discussed. In particular, the impedance represented by the T-network **183** and/or the π-network **186** are forms of the equivalent circuit **163** (FIG. **4**B).

Referring next to FIGS. **7**A and **7**B, shown are an example schematic of both a T-network **183*a*** and a π-network **186*a*** that may be employed in various embodiments of the present invention. In this respect, the T-network **183*a*** includes series inductance L that is shown as two separate series inductances L/2. In addition, the T-network **183*a*** also includes a shunt capacitance C. The T-network **183*a*** includes a series loss resistances R and a shunt conductance G that are inherent in the conductors making up the inductances L/2, the capacitance C, and the electrical wire connecting such components.

The π-network **186*a*** includes a series inductance L and shunt capacitances C/2. For multiple π-networks **186*a*** that are coupled together in series, adjacent shunt capacitances C/2 may be added together to become capacitance C. The π-networks **186*a*** also includes a series resistance R and a shunt conductance G that are inherent in the conductors making up the inductance L, the capacitances C/2, and the electrical wire connecting such components. The T-network **183*a*** and π-network **186**a illustrate more particular embodiments of the T-networks **183** or π-networks **186**.

Turning then, to FIG. **8**, shown is an example of a power multiplier **200** according to an embodiment of the present invention. The power multiplier **200** includes a power multiplying network **203** and a launching network **206**. The launching network **206** also includes a directional coupler **209** that couples the launching network **206** to the power multiplying network **203**. A power source **213** is coupled to the launching network **206**. Also, the launching network **206** is terminated in a matching load R_L.

In one embodiment, the power multiplying network **203** is a multiply-connected, velocity inhibiting circuit constructed from a number of lumped-elements **216**. As contemplated herein, the term "network" is defined as an interconnected structure of electrical elements. The terms "multiply-connected" is a mathematical term describing the existence of a closed path in a resonator, waveguide, or other electrical structure that cannot be reduced to a point without part of the closed path passing through regions that are external to the geometrical boundaries of the resonator, waveguide, or other electrical pathway. The power multiplying network **203** is "velocity inhibiting" as the electrical structure of the power multiplying network **203** results in a reduced velocity of propagation of an electromagnetic wave through the power multiplying network **203** relative to the speed of an electromagnetic wave through free space, which is the speed of light.

In addition, the term "lumped" is defined herein as effectively concentrated at a single location. Thus, the terms "lumped-elements" refer to discrete, two-terminal, concentrated electrical elements such as capacitance, inductances, resistance, and/or conductance. Thus, the lumped-elements as described herein may comprise discrete inductors, capacitors, or resistors. In addition, as contemplated herein, lumped-elements may also comprise diodes, transistors, and other semi-conductors that may be described, for example, as nonlinear resistors or conductors that have resistance or conductance that is controlled by the polarity of applied voltages or currents, etc. In addition, lumped-elements may also comprise inherent capacitances, inductances, resistances, or conductances of various electrical structures such as helices, parallel plates, or other structure as will be discussed. Similar to the power multiplying network **203**, the directional coupler **209** is also constructed using lumped-elements.

The power multiplying network **203** is a velocity inhibiting circuit that results in a slower velocity of propagation of an electrical disturbance such as a traveling wave. In this respect, the power multiplying network **203** has an electrical length that is equal to an integer multiple of the wavelength of the operating frequency of the power source **213**. Due to the velocity inhibited nature of the power multiplying network **203**, its size is quite compact in comparison with the wavelength of the operating frequency of the power source **213**. In addition, the direction coupler **209** causes a phase shift that is equal to one quarter of the wavelength of an exciting traveling wave generated by the power source **213** at the operating frequency as will be discussed.

In one embodiment, the power multiplying network **203** is constructed from lumped-elements **216** such as, for example, the inductances L and capacitances C as shown in FIG. **8**. In one embodiment, the inductances L may be actual inductors and the capacitances C may be actual capacitors that are either commercially available or may be constructed as needed. For example, the power multiplying network **203** may be characterized as a ring of interconnected T-networks **183**a (FIG. **7**A) or π-networks **186**a (FIG. **7**B), although the interconnected T-networks **183**a (FIG. **7**A) or π-networks **186**a (FIG. **7**B) may be arranged in a multiply-connected structure other than a ring. Each of the T-networks **183**a or π-networks **186**a may be considered a "section" of the power multiplying network **203**. In this respect, assuming that the power multiplying network **203** comprises a number of T-networks **183**a, then each inductance L may be divided into two series inductances L/2 that make up the series inductances L/2 as described in the T-network **183**a (FIG. **7**A). Similarly, assuming that the power multiplying network **203** comprises a number of π-networks **186**a, each capacitance C may be also be viewed as a pair of shunt capacitances C/2, each such shunt capacitance C/2 making up one of the shunt capacitances C/2 of the π-network **186**a (FIG. **7**B). Whether T-networks **183**a or π-networks **186**a are employed to create the sections of the power multiplying network **203**, each of the networks **183**a or **186**a results in a predefined phase shift ϕ_S.

Assuming that either T-networks **183**a or π-networks **186**a are to be employed to construct the power multiplying network **203** at some frequency f and some quality factor Q, then values for the lumped elements **216** such as the inductances L and capacitances C or other lumped elements are determined. The quality factor Q is defined conventionally as

$$Q=f/\Delta f.$$

Such values may be calculated from the known characteristic impedance Z_o and the transmission line complex propagation constant γ of a predetermined portion of the hypothetical transmission line **101** (FIG. **3**) of the hypothetical power multiplier **100**a. In this respect, the characteristic impedance Z_o and the transmission line complex propagation constant γ may be calculated for a predefined unit length of the hypothetical transmission line **101** as follows:

$$Z = R_T + j\omega L_T,$$

$$Y = G_T + j\omega C_T,$$

$$\begin{aligned} Z_o &= \sqrt{Z/Y} \\ &= \sqrt{(R_T + j\omega L_T)/(G_T + j\omega C_T)}, \text{ and} \\ \gamma &= \sqrt{ZY} \\ &= \sqrt{(R_T + j\omega L_T)(G_T + j\omega C_T)}, \end{aligned}$$

where Z is the series impedance per unit length of transmission line, Y is the shunt admittance per unit length of transmission line. In the low loss case (i.e. $R_T \approx 0$ and $G_T \approx 0$), the characteristic impedance reduces to

$$Z_o=\sqrt{L_T/C_T}.$$

In addition, the velocity of propagation may be calculated as

$$v = \frac{1}{\sqrt{L_T C_T}}.$$

In order to determine values for R_T, L_T, G_T, and C_T, for a given section of transmission line **159**, various references may be consulted that provide such information such as, for example, Terman, F. E., *Radio Engineering Handbook*, McGraw-Hill, 1943, pp. 172-178, 191-215, or other references as can be appreciated.

Once the characteristic impedance Z_o for a predefined portion of the hypothetical transmission line **101** is known, then the complex electrical length θ of the predefined portion of the hypothetical transmission line **101** is calculated as

$$\theta=\gamma l$$

where l is the physical length of the predefined portion of the hypothetical transmission line **101**. Given the characteristic impedance Z_o, the transmission line complex propagation constant y, and the electrical length θ of the predefined portion of the hypothetical transmission line **101**, the series impedances Z_1 and Z_2, and the shunt impedance Z_3 of the T-network **183** (FIG. **6**A) may be calculated as follows:

$$Z_1=Z_2=Z_o \tan h(\theta/2), \text{ and}$$

$$Z_3=Z_o/\sin h(\theta).$$

Alternatively, the shunt impedances Z_A and Z_B, and the middle impedance Z_C of the π-network **186** may be calculated as follows:

$$Z_A=Z_B=Z_o \cot h(\theta/2), \text{ and}$$

$$Z_C=Z_o \sin h(\theta).$$

Once the series impedances Z_1 and Z_2, and the shunt impedance Z_3 of the T-network **183**, or the shunt impedances Z_A and Z_B, and the middle impedance Z_C of the π-network **186** are known, then corresponding values for L and C may be determined. Assuming, for example, that one has calculated the shunt impedances Z_A and Z_B, and the middle impedance Z_C of the π-network **186**, then inductance L associated with the middle impedance Z_C may be calculated therefrom where

$$Z_C=r+j\omega L.$$

Also, the capacitance C associated with the shunt impedances Z_A and Z_B may be calculated where

$$Z_A = Z_B = \frac{1}{j\omega C}.$$

It may be the case that L and C are too large to be practically represented in the form of a lumped element **216**. If such is the case, then a reverse calculation or reverse mapping may be performed using known values for L and C to determine how much of the hypothetical transmission line **101** may be represented by a given T-network **183** or π-network **186**. In this respect, one may determine how many T-networks **183** or π-networks **186** may necessarily be employed in a given power multiplying network **203**. In this respect, values may be chosen for L and C in view of the calculated values for L and C identified above.

Assuming that the series impedances Z_1 and Z_2, and the shunt impedance Z_3 of the T-network **183** are calculated from predetermined values for L and C, then the characteristic impedance Z_o and the transmission line complex propagation constant γ**0** may be calculated as follows:

$$Z_o = \sqrt{Z_1(Z_1+2Z_3)}, \text{ and}$$

$$\gamma = \text{Arctanh}\left(\frac{\sqrt{Z_1(Z_1+2Z_3)}}{Z_1+Z_3}\right).$$

Alternatively, assuming that the shunt impedances Z_A and Z_B, and the middle impedance Z_C of the π-network **186** are calculated from predetermined values for L and C, then the characteristic impedance Z_o and the transmission line complex propagation constant γ may be calculated as follows:

$$Z_o = Z_A\sqrt{\frac{Z_C}{Z_C+2Z_A}}, \text{ and}$$

$$\gamma = \text{Arctanh}\left(\frac{\sqrt{Z_C(Z_C+2Z_A)}}{Z_A+Z_C}\right).$$

Once the length I of the hypothetical transmission line **101** that is represented by a specified T-network **183** or π-network **186** is known, then one can determine how many similar T-networks **183** or π-networks **186** are needed to simulate the impedance of the entire hypothetical transmission line **101**. Thus, by performing the forward and reverse calculations described above, one can determine general values for the inductances L and capacitances C of the power multiplying network **203**.

In addition, the power multiplying network **203** further comprises a phase shifter **219**. The phase shifter **219** comprises a circuit constructed from lumped-elements that is combined in series with a portion of the directional coupler **209** to make up the inductance L of the specific section within which the directional coupler **209** is located.

The power multiplying network **203** also includes a diverter **223** that couples the power multiplying network **203** to a load **226**. The diverter **223** is defined herein as an electrical element or circuit that may be employed to divert or redirect all or a portion of a traveling wave from the power multiplying network **203** to the load **226**. In this respect, the diverter **223** may comprise, for example, a switch, relay, solid state switch, plasma switch, or other device with like capability. The diverter **223** may also be a circuit that presents an electric window that is biased using a predefined control voltage or current to divert the energy within a traveling wave to the load **226**, depending upon the state of the control voltage or current, etc.

During operation, the power source **213** is employed to launch an exciting traveling wave in the launching network **206**. The exciting traveling wave may be, for example, a sinusoidal wave or other appropriate shape. The directional coupler **209** couples at least a portion of the exciting traveling wave from the launching network **206** into the power multiplying network **203**, thereby resulting in a traveling wave that propagates within the power multiplying network **203**. Given that the electrical length of the power multiplying network **203** is an integer multiple of the wavelength of the power source **213** and that the directional coupler **209** is equal to ¼ of the wavelength of the power source **213**, then the traveling wave that propagates within the power multiplying network **203** is continually reinforced by the portion of the exciting traveling wave that is coupled into the power multiplying network **203**. Also, the traveling wave propagates in a single direction around the power multiplying network **203**. This results in power magnification M of the power of the traveling wave by a predefined factor that may be many times greater than the power of the power source **213**, depending upon the losses and tolerances of the lumped-elements **216** and other factors.

Both the exciting traveling wave launched into the launching network **206** and the traveling wave that propagates around the power multiplying network **203** may be AC power signals such as electrical power signals generated at 50 Hertz, 60 Hertz, 400 Hertz, or any other power frequency as can be found in the electrical generation systems in the United States and countries around the world. However, in any event, the frequency of the exciting traveling wave, the traveling wave, and the power source **213** may be any frequency possible, although they typically correspond to frequencies with wavelengths for which the closed path length of the power multiplying network **203** is approximately 1/10 the wavelength or less of the traveling wave.

When the exciting traveling wave is applied to the launching network **206**, the power of the traveling wave continually increases with time until it reaches a maximum power. The maximum power is reached when the losses in the power multiplying network **203** plus the losses in the matching load R_L are equal to the power supplied by the power source **213**. When the maximum power is reached, the diverter **223** may be actuated to direct the traveling wave from the power multiplying network **203** to the electrical load **226**. In a typical situation, it may take up to approximately a dozen cycles to reach maximum power in the power multiplying network **203**, although it is possible that maximum power may be reached in more or less cycles. Alternatively, the diverter **223** may be actuated to direct the traveling wave from the power multiplying network **203** at any time deemed appropriate such as, for example, when the energy accumulated in the power multiplying network **203** reaches any predefined threshold, etc.

The power multiplier **200** provides significant advantages in that it facilitates real power multiplication at lower power frequencies such as the operating frequencies of electrical power distribution systems around the world that operate, for example, at 50 Hertz, 60 Hertz, 400 Hertz, or other low frequencies. The velocity inhibiting nature of the power multiplying network **203** facilitates the creation of a power multiplier **200** that can operate at such low power generation frequencies with astonishing size reduction. That is to say, where prior theory may have taught that power multipliers operating at conventional power generation frequencies might have required a hypothetical waveguide that extended for thousands of kilometers as discussed with reference to FIG. **3**, now the same can be created in a compact size that fits, for example, in a small room.

The velocity of propagation of the traveling wave through the power multiplying network **203** relative to the velocity of a traveling wave through free space is described herein as the velocity factor. The velocity inhibiting nature of the power multiplying network **203** provides for velocity factors that are on the order of 1/1,000,000, although even smaller velocity factors may be achieved.

In addition, the power multiplier **200** may further include a number of launching networks **206**, each launching network **206** being coupled to the power multiplying network **203** by a directional coupler **209**. Such a configuration would facilitate a corresponding increase in the rate at which the power of the traveling wave accumulates during operation of the power multiplier **200**.

In an alternative embodiment, the traveling wave may be a solitary wave that propagates around the power multiplying network **203**. In order to propagate a solitary wave around the power multiplying network **203**, the power multiplying network **203** is constructed so as to include nonlinear elements such as, for example, diodes, transistors, or other active components so as to be nonlinear and dispersive. Thus, nonlinear components are defined herein as components that provide an output having an amplitude that is not linearly proportional to the input as can be appreciated by those with ordinary skill in the art. By constructing the power multiplying network **203** from a suitable network of nonlinear elements and/or a combination of linear and nonlinear elements, a solitary wave may be propagated around the power multiplying network **203**. In this respect, the power source **213** would be a pulse generator that generates and launches an exciting traveling wave into the launching network **206**. To achieve power multiplication, a solitary exciting traveling wave would have to be spatially synchronized with the solitary traveling wave. In addition, the launching network **206**, the directional coupler **209**, and the phase shifter **219** may be constructed to include elements that are nonlinear and dispersive in nature to facilitate the propagation of solitary waves there through.

It should be appreciated that as the gain of the power multiplying network **203** increases, its quality factor Q rises and its bandwidth BW narrows around the operating frequency. In one embodiment, this may be a desirable asset for a strictly monochromatic system. Should broader bandwidths BW be desired, the electrical bandwidth BW of the power multiplying network **203** may be tailored for the specific application. For example, low-loss power multiplying networks **203** with broader and controlled-shape passbands may be constructed following various electrical filter design. See for example, Matthaei, G. L., L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks, and Coupling Structures*, McGraw-Hill, 1964; and Fano, R. M., *Theoretical Limitations on Broadband Matching of Arbitrary Impedances*, Journal of the Franklin Institute, Vol. 249, 1950, pp. 53-83 and 129-155.

In another embodiment, the power multiplier **200** as described above may also be constructed incorporating so called "Tracking-Filter" design techniques such that the electrical passband of the power multiplier **200** can be dynamic and automatically controlled to coherently track frequency and phase variations of the power source **213** while maintaining the desired operational properties described above. In implementing a power multiplier **200** with a dynamic electrical passband, the frequency of the power source **213** is monitored and compared with the resonant frequency of the power multiplying network **203**. An error signal may be generated from such a comparison and employed in a feedback loop to dynamically modify the ring component parameters such as the lumped-elements of the power multiplying network **203** to tune it to the spectral variations of the power source **213**. In such case, the lumped-elements described above may be parametrically dynamic with variable parameters as can be appreciated.

Referring next to FIG. **9**, shown is a schematic that provides one example of the phase shifter **219** according to an aspect of the present invention. The phase shifter **219** comprises a T-network **183***a* (FIG. **7**A), although a π-network **186***a* may be employed as well. In this respect, the phase shifter **219** includes series inductances L_T and a shunt capacitance C_T. In this respect, the phase shifter **219** is constructed from lumped-elements as part of the power multiplying network **203**.

The series inductances L_T and the shunt capacitance C_T are specified so as to result in a phase shift ϕ_S. The series inductances L_T and/or the shunt capacitance C_T (assuming that a T-network **186***a* is employed) may be variable so as to allow the phase shift ϕ_S to be adjusted as necessary to compensate for any inaccuracies in the phase shifts ϕ_S of each section and in the phase shift θ of the directional coupler **209**. This is done to ensure that the total phase shift presented by the power multiplying network **203** is an integer multiple of 360 degrees for the wavelength of the power source **213**. The specific calculations that are performed to determine the values of the inductances L_T and the shunt capacitance C_T will be discussed.

With reference to FIG. **10**, shown is a schematic that illustrates an example of the directional coupler **209** according to an aspect of the present invention. The directional coupler **209** comprises a number of lumped-elements such as capacitors C_{LC} and C_{TC} and/or the elements of π-neteworks **233** and **236**. Such a directional coupler **209** ensures that the traveling wave propagates in a single direction along the power multiplying network **203** and to achieve the reinforcement of the traveling wave with the portion of the exciting traveling wave that propagates through the launching network **206**.

With the foregoing discussion of the power multiplying network **203**, the directional coupler **209**, and the phase shifter **219**, the total phase shift presented by the power multiplying network **203** may be determined as follows:

$$\phi_{PMW}=\phi_s(N-1)+\phi+\theta,$$

where N is equal to the number of sections in the power multiplying network **203**.

In addition, the diverter (FIG. **8**) may be constructed in a manner similar to the directional coupler **209** in which the values of the coupling capacitances are used to control the rate at which energy exists the power multiplying network **203**.

Referring next to FIG. **11**, shown is a schematic of a power multiplier **250** according to another embodiment of the present invention. The power multiplier **250** includes a power multiplying network **253** that is constructed from a toroidal helix as shown, or any of its variants comprising left handed, right handed, or superpositions of left and right handed helices as taught by Canadian Patent 1,186,049, U.S. Pat. No. 4,622,558, and U.S. Pat. No. 4,751,515, each of these references being filed by James F. Corum, the entire text of each of these references being incorporated herein by reference. In this respect, the toroidal helix includes the inductances L (FIG. **8**) by virtue of its construction. In addition, the impedance presented by the toroidal helix includes capacitances as can be appreciated by those with ordinary skill in the art. (see Krause, John D., *Antennas*, McGraw-Hill, 1st edition, 1950, FIG. 7.2). The power multiplier **250** includes a launching network **256** that is coupled to the power multiplying network **253** by a directional coupler **259**. The power multiplier **250** also includes the diverter **223** that couples an output from the power multiplier **250** to a load **226** as shown. The power source **213** is coupled to the launching network **256** and launches an exciting traveling wave into the launching network **256** in a similar manner as was described with reference to the power multiplier **200**. Similarly, the launching network **256** is terminated in a matching load R_M.

The directional coupler **259** may be, for example, a section of the helix or even a π-network **186** (FIG. 7B) as shown. The directional coupler **259** imposes a phase shift of ¼ of the wavelength of the exciting traveling wave in a similar manner as was described above.

The operation of the power multiplier **250** is substantially similar as was discussed with reference to the power multiplier **200** of FIG. **8**. The power multiplier **250** illustrates that fact that the power multiplying network **253** may comprise one or more electrical structures such as a toroidal helix, two or more cross-wound helices, a contrawound helix, or other electrical structures that include inherent capacitances and inductances that act as the lumped elements **216** (FIG. **8**) such as the inductances L (FIG. **8**) and capacitances C (FIG. **8**).

With reference back to FIG. **8**, once we have determined the values for the inductances L and capacitances C per section of the power multiplier **200** that comprises T-networks **183** (FIG. **6**A) or π-networks **186** (FIG. **6**B), then actual power magnification that can be achieved by the resulting power multiplier **200** given the values for the lumped-elements (i.e. the shunt capacitances C and the series inductances L) may be determined. Specifically, the lumped-elements are specified to achieve a predefined phase shift per section at the predefined operating frequency.

The progression of calculations that is performed to determine the values for the lumped elements **216** such as the capacitances C and inductances L of the power multiplier **200** is now discussed. In the follow calculations, the assumption is made that each section of the power multiplying network **203** comprise π-networks **186** (FIG. **6**B). To begin, the operating frequency f of the power multiplier **200** is specified. Also, both the inductance L and capacitance C of each section of the power multiplying network **203** are specified based upon the values for such elements identified above. In addition, a quality factor Q is specified for the inductances L of each section of the power multiplying network **203**. The frequency in terms of radians/sec is calculated as

$$\omega=2\pi f \text{ radians/sec.}$$

Also, the resistance in each of each inductance L is calculated as

$$r=\frac{\omega L}{Q}\,Ohms.$$

Thereafter, the impedance Z_C is calculated as follows:

$$Z_C=r+i\omega L \text{ Ohms},$$

where "i" represents $\sqrt{-1}$ as is known by those with ordinary skill in the art. Given the capacitances C specified above, the shunt impedances Z_A and Z_B are calculated as follows:

$$Z_A=Z_B=\frac{1}{i\omega C}\,Ohms.$$

Next, the characteristic impedance Z_0 is calculated as follows:

$$Z_0=Z_A\sqrt{\frac{Z_C}{(Z_C+2Z_A)}}\,Ohms.$$

The characteristic impedance is defined as the ratio of the forward wave voltage over the forward wave current. In this respect, a physical measurement of the characteristic impedance of each section may be taken and compared with the calculated characteristic impedance Z_0 to verify the accuracy thereof.

In addition, the propagation constant y per section is calculated as follows:

$$\gamma=a\tanh\left[\frac{\sqrt{Z_C(Z_C+2Z_A)}}{(Z_A+Z_C)}\right].$$

The Attenuation Constant α per section and the Phase Constant β per section are defined as

$$\alpha_{section}=\mathrm{Re}(\gamma) \text{ Nepers/section, and}$$

$$\beta_{section}=\mathrm{Im}(\gamma) \text{ radians/section.}$$

The phase shift per section may then be calculated as

$$\phi=(57.296 \text{ Deg/Rad})\beta_{section} \text{ Degrees.}$$

The velocity of the traveling wave in sections per second propagating along the power multiplying network **203** is calculated as

$$v = \frac{\omega}{\beta_{section}} \text{ sections/second.}$$

Next, the electrical circumference C_λ of the power multiplying network **203** is specified in terms of wavelengths at the operating frequency in degrees as

$$C_{Deg}=C_\lambda(360 \text{ Degrees/wavelength) Degrees.}$$

Next, the number of sections N (either T-networks or π-networks) is calculated as

$$N = \frac{C_{Deg}}{\phi}.$$

Once the number of sections N is known, then the loss resistance R_C around the closed path of the power multiplying network **203** may be calculated as

$$R_C=Nr \text{ Ohms.}$$

where r is as defined above. The field propagation decay A for a single traversal of the power multiplying network **203** may be calculated as

$$A=e^{-\alpha_{section}N}.$$

The attenuation A_{dB} around the power multiplying network **203** is calculated as

$$A_{dB}=-20 \log(A).$$

The pulse duration T of a peripheral disturbance is calculated as

$$\tau = \frac{N}{v} \text{ seconds.}$$

The power magnification M of the power multiplier **200** at optimum coupling is calculated as

$$M = \frac{1}{(1-A^2)}.$$

The power magnification M_{dB} expressed in decibels is calculated as

$$M_{dB}=10 \log(M).$$

The optimum coupling C_{opt} is calculated as

$$C_{Opt}=1-A^2.$$

The optimum coupling C_{opt} is calculated in decibels (dB) as

$$C_{optdB}=10 \log(C_{opt)\ dB.}$$

In addition, a useful reference that may be consulted to determine the various elements of the directional coupler **209** and the phase shifter **219** is Matthaei, G. L., L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks, and Coupling Structures*, McGraw-Hill, 1964, (see Chapter 14). While specific circuit designs may be discussed herein that may be employed as the directional coupler **209** and the phase shifter **219**, it is understood that other circuit designs and circuit structures may be employed as well, such alternative designs falling within the scope of the present invention.

Referring next to FIG. **12**, shown is the power multiplier **200** coupled to a power distribution network **300** according to one embodiment of the present invention. While the power multiplier **200** that employs the power multiplying network **203** is shown in FIG. **12**, it is understood that other embodiments of power multipliers as described herein such as the power multiplier **250** may be employed, where the power multiplier **200** and the power multiplying network **203** are described herein merely as an example.

The power distribution network **300** may be, for example, a power grid such as the North American power grid or other power grids anywhere in the world. As shown in FIG. **12**, the launching network **206** is coupled to the power distribution network **300**. The output of the diverter **223** is also coupled to the power distribution network **300**.

The diverter **223** receives a load feedback **303** that may comprise, for example, a load feedback signal generated based upon a current electrical load on the power distribution network **300**. The directional coupler **209** may be selectively coupled to the launching network **206**, or the launching network **206** may be selectively coupled to the power distribution network **300** in order to facilitate a controlled power input into the power multiplying network **203** from the power distribution network **300**, thereby resulting in storage of power in the power multiplying network **203** of the power multiplier **200**. Alternatively, the directional coupler **209** may be configured to control the rate at which power is input into the power multiplying network **203**. By virtue of the fact that the launching network **206** and the diverter **223** are both coupled to the power distribution network **300**, the power multiplying network **203** may be employed to store power from the power distribution network **300** and to supply power to the power distribution network **300** as desired.

The diverter **223** may be configured to control the output of the power multiplying network **203** in response to the load feedback **303**. In this respect, the power stored in the power multiplying network **203** may be supplied, for example, to the power distribution network **300** to provide power upon an occurrence of an abrupt increase in the electrical load associated with the power distribution network **300**.

Given that utilities that supply power to power distribution networks **300** can experience severe mismatches between peak and average load demands, the power multiplying network **203** may advantageously be employed for "power smoothing." For example, the power multiplying network **203** may be employed in locations local to electrical loads that may be remote from power generation stations to "smooth" brown outs and black outs by utilities with large peak-to-average load demands. In this respect, the power multiplying network **203** may be coupled to various locations of power distribution networks **300** to provide local controlled smooth transition between load states by providing for temporary energy storage that may be drawn upon as needed.

This may reduce the electro-mechanical stress on existing power generation equipment in electrical generation stations. Specifically, when large load swings and transients occur on the power distribution systems **300**, significant electromechanical stresses can occur in rotating machinery used in power generation. For example, either a one time occurrence of a large transient or the repeated occurrences of smaller transients over time can result in the catastrophic failure of shafts and other mechanical components of electrical generators. Also, electrical wiring failure can occur in generators and at other points in electrical distribution systems. In addition, load swings and transients can affect the frequency and phase stability of electrical generators as they react to the changes in electrical loads. The power multiplying network can be employed to eliminate such stresses on power generation and distribution equipment, and can ensure frequency and phase stability in the existing power distribution networks **300**.

In circumstances where there exists an intervening electrical load point such as a city between electrical generation stations and a remote load, it is possible that during heavy load times, the demanded throughput cannot be conveyed from the electrical generation station to the remote load through the intervening electrical load point. Thus, a power multiplier **200** that includes the power multiplying network **203**, for example, may be employed to address the "rush hour" electrical traffic congestion problem around such intervening load point. For example, the power multiplying network **203** may be coupled to the power distribution network **300** near the intervening load point to provide for storage of power that can be accessed at such heavy traffic times, thus smoothing the demand and preventing loss of service at the remote load.

To facilitate effective power smoothing on a given power distribution network **300**, one or more power multiplying networks **203** may be coupled to demand stressed portions of a given power distribution network **300**. As described above, such demand stressed portions of a power distribution network **300** may be at locations near cities or other large loads that experience large peak-to-average load demands. Also, such demand stressed portions may be near intervening electrical load points. Additionally, other locations of various power distribution networks **300** may be demand stressed as will be appreciated.

The various embodiments of the power multipliers described herein, including the power multiplier **200** employing the power multiplying network **203**, are ideal for power smoothing on a power distribution network **300** since the power stored in such power multiplying networks is available on a near instantaneous basis. Consequently, the power multiplying network **203** may be employed, for example, to supply power when generating equipment on the power distribution network **300** cannot react fast enough to compensate for abrupt changes such as increases in the electrical load. In this respect, one or more power multiplying networks **203**, for example, may be employed to supply power to the power distribution network **300** for periods of time to facilitate the adjustment of power generation systems coupled to the power distribution network to supply power to the increased electrical load after the occurrence of the abrupt increase.

With reference to FIG. **13**, shown are several power multipliers **200/250** that employ power multiplying networks **203/253** coupled to the power distribution network **300** according to another embodiment of the present invention. While the power multiplying networks **203/253** are shown, other embodiments of the power multiplying networks may be employed as can be appreciated. A power multiplier control system **206** is provided with outputs that are electrically coupled to each of the diverters **223** of the respective power multipliers **200/250**.

The power multiplier control system **206** generates control outputs that are applied to the diverters **223** to control the release of power from each of the power multiplying networks **203/253** to the power distribution network **300** in response to the load feedback from the power distribution network **300**. In one embodiment, the power multiplier control system **206** is configured to apply power from each of the power multiplying networks **203/253** to the power distribution network **300** in a sequential order. In this respect, the period of time that the power distribution network **300** may be supplied with power from the power multiplying networks **203/253** is increased based upon the number of power multiplying networks **203/253** employed. In this respect, multiple power multiplying networks **203/253** may be employed to provide adequate time for generating equipment to adjust to changing electrical loads without stressing the mechanical and electrical components of the generating equipment. Alternatively, the power stored in multiple ones of the power multiplying networks **203/253** may be applied to the power distribution network **300** concurrently to meet extreme load increases.

Furthermore, the elements that are employed to construct the various embodiments of the power multiplying networks **203/253** described herein may be constructed using low loss and high permittivity dielectrics in capacitances, and low loss conductors in the inductances (such as inductance coils). Such low loss conductors may be, for example, cryogenic conductors and/or superconductors. Such low loss conductors allow for much greater storage capacity at extremely high efficiencies. Specifically, given that power storage will increase in the power multiplying networks **203/253** as described herein until the losses experienced in the power multiplying networks **203/253** equal the power input, where a given power multiplying network is constructed of extremely low loss conductors, it follows that very large amounts of power may be stored.

Power Multiplication and Parametric Excitation

With reference to FIGS. **14** and **15**, shown are drawings of power multipliers **400***a* and **400***b* that employ parametric excitation according to various embodiments of the present invention. The power multipliers **400***a* and **400***b* each include a respective power multiplying network **403***a* and **403***b* and a launching network **406**. Each of the power multiplying networks **403***a*/**403***b* comprises a ring as mentioned above. The launching network **406** also includes a directional coupler **409** that couples the launching network **406** to the respective power multiplying networks **403***a*/**403***b*. A power source **413** is coupled to the launching network **406**. Also, the launching network **406** is terminated in a matching load R_L.

In addition, the each of the power multiplying networks **403***a*/**403***b* further comprises a phase shifter **419**. The phase shifter **419** comprises a circuit constructed from lumped-elements that is combined in series with a portion of the directional coupler **409** to make up the inductance L(t)/L of the specific section within which the directional coupler **409** is located.

Each of the power multiplying networks **403***a*/**403***b* also includes a diverter **423** that couples the respective power multiplying network **403***a*/**403***b* to a load **426**. The diverter **423** is defined herein as an electrical element or circuit that may be employed to divert or redirect all or a portion of a traveling wave from one of the power multiplying networks **403***a*/**403***b* to the load **426**. In this respect, the diverter **423** may comprise, for example, a switch, relay, solid state switch, plasma switch, or other device with like capability. The diverter **423** may also be a circuit that presents an electric window that is biased using a predefined control voltage or current to divert the energy within a traveling wave to the load **426**, depending upon the state of the control voltage or current, etc.

In the embodiment shown in FIGS. **14** and **15**, each of the power multiplying networks **403***a*/**403***b* is constructed from reactances **416** and parametric reactances **418** that, according to one embodiment, comprise lumped-elements. As shown in FIG. **14**, the reactances **416** comprise capacitances C (FIG. **14**) and inductances L (FIG. **15**) and the parametric reactances **418** comprise parametric inductances L(t) (FIG. **14**) and parametric capacitances C(t). Alternatively, the parametric reactances **418** in a single power multiplier may include both parametric inductances L(t) and parametric capacitances C(t).

In one embodiment, the parametric reactances **418** such as the parametric inductances L(t) or the parametric capacitances C(t) may comprise linear or non-linear reactances. Thus, the parametric inductances L(t) may comprise linear or non-linear inductances and the parametric capacitances C(t) may comprise linear or non-linear capacitances. As described herein, a linear circuit component is one in which the impedance of the circuit component is not a function of the magnitude of a voltage signal in the circuit component.

Examples of linear reactances may comprise, for example, conventional air-core coils of wire, capacitors, and similar lossless passive circuit elements composed of media with linear permeability (μ) and linear dielectric permittivity (∈). Sections of transmission lines (and waveguides) constructed of linear media may also supply examples of linear reactances as viewed at their inputs.

Examples of non-linear reactances may comprise reactive elements with a nonlinear impedance relationship between voltage and current. Such reactive elements may include saturable reactors, varactor (varicap) diodes with voltage variable junction capacitance, and elements constructed of nonlinear permittivity [∈=∈(V), where permittivity is a function of voltage] or nonlinear permeability [μ=μ(I), where permeability is a function of current], as is the case in transmission line elements with magnetically biased ferrites, and even plasma media.

Time-varying reactive elements also occur in engineering practice. Common examples of time-varying reactances are inductors and capacitors whose permittivity and permeability functions are pumped in time by a control voltage or current. Similarly, distributed time-varying impedances have their constitutive parameters pumped by a control signal, which may be electrical, electromagnetic, optical, thermal, mechanical, acoustical, etc.

The power multipliers **400***a* and **400***b* are operated in order to multiply power in much the same way as the power multipliers **200** (FIG. **8**) or **250** (FIG. **11**) with the exception that the parametric reactances **418** are varied in time as will be described below. As a result of the variation of the parametric reactances **418**, a negative resistance is introduced into the power multiplying networks **403***a*/**403***b* that effectively electrically negates the physical resistance inherent in the components of the power multiplying networks **403***a*/**403***b*. Consequently, the power multipliers **400***a*/**400***b* can accumulate a drastically greater amount of power in a traveling wave within the power multiplying networks **403***a*/**403***b*. In the case that the physical resistance of a respective power multiplying network **403***a*/**403***b* is almost completely negated, then the power multiplying network **403***a*/**403***b* may actually approach superconductivity.

Recall as described above that in a power multiplier **200** (FIG. **8**) that does not employ parametric excitation (does not make use of parametric reactances), power will continue to build up in the power multiplying network **203** (FIG. **8**) (or the ring) during operation until the losses due to the inherent resistance of the power multiplying network **203** plus the losses in the matching load RL that terminates the launching waveguide **406** is equal to the power generated by the power source **413**. Given the use of parametric reactances **418** in the power multiplying networks **403***a*/**403***b*, the physical resistance of the power multiplying networks **403***a*/**403***b* are negated by the negative resistance introduced due to the parametric excitation of the parametric reactances.

Thus, if the physical resistance was reduced due to the negative resistance injected in the power multiplying networks **403***a*/**403***b*, the power of the traveling wave in the power multiplying networks **403***a*/**403***b* will continue to build up until the losses due to the reduced physical resistance and due to the matching load equal the power generated by the power source **413**. As the negative resistance injected into a power multiplying network **403***a*/**403***b*approaches the total physical resistance of a respective one of the power multiplying networks **403***a*/**403***b*, then the power multiplying networks **403***a*/**403***b* approach superconductivity. However, it may be the case that there are limits to how closely the negative resistance can approach the actual physical resistance of the respective power multiplying network **403***a*/**403***b*, where the actual amount of negative resistance depends upon the magnitude and phase of the variation in the parametric reactances that make up part of the power multiplying network **403***a*/**403***b*. Thus, the actual amount of negative resistance generated is application specific.

According to the various embodiments, one or more parametric reactances **418** in the power multiplying networks **403***a*/**403***b* are varied in time at a frequency that is in a predefined relationship relative to the operating frequency of the power source **413**. That is to say, the frequency of at which the parametric reactances **418** are varied in time is in a predefined relationship relative to the frequency of a traveling wave in the ring of the power multiplier **400***a*/**400***b*.

To explain further, if a signal at frequency f_s is injected into a linear, tuned circuit such as an LC circuit, which has a reactive element changing at frequency f_p (called the "pump" frequency), a new mixer frequency (called the idler frequency, f_i) will appear in the circuit. The relation between these three frequencies is as follows:

$$f_i = mf_p \pm nf_s.$$

If the reactance element is varied at a frequency f_p (the pump frequency) in a 2:1 ratio to the resonant frequency (which is also tuned to the signal frequency f_s) of the circuit, then the difference or idler frequency f_i will be the same as the signal frequency f_s.

If the operating point of the reactance element is varied at one frequency, and an oscillator signal is coupled into the circuit at another frequency, under certain conditions between the two frequencies, the circuit impedance, instead of being a pure imaginary, will become complex. The imaginary component could correspond to an inductive reactance, but a negative real part can arise, effectively corresponding to a negative resistance injected into the circuit. The amount of negative resistance injected into the circuit is controlled by the relative magnitude and phase at which the reactance element is varied.

According to various embodiments, the negative resistance arises when the pump frequency f_p is equal to twice the signal frequency f_s of the circuit. In this "degenerate" mode of operation, where both m and n=1 and $f_p = 2 \times f_s$, the idler frequency f_i is equal to the signal frequency f_s. Therefore, when the pump frequency f_p is equal to twice the signal frequency ($2 \times f_s$), a negative resistance is injected into the circuit.

According to the various embodiments of the present invention, which, by design, possess small dissipation, the parametric reactances **418** are varied at a frequency that is twice the frequency of the power source **413** (and the generated traveling wave flowing through the ring) of the power multiplier **400**_a_/**400**_b_. When this condition is met, the parametric reactance effectively negates at least a portion of the physical resistance inherent in the power multiplying networks **403**_a_/**403**_b_. The degree to which the physical resistance inherent in the power multiplying networks **403**_a_/**403**_b_ is negated depends upon the magnitude of the negative resistance generated by the operation of the parametric reactances. The magnitude of the negative resistance depends upon the magnitude and phase of the variation of the parametric reactances **418** and is design specific as described above.

While, in one embodiment, a ratio of 2:1 is specified between the frequency of variation of the parametric reactances **418** and the frequency of the power source **413** (or traveling wave in the ring) in order to generate the negative resistance in the power multiplying networks **403**_a_/**403**_b_, it is understood that other frequency relationships between the frequency of variation of the parametric reactances **418** and the frequency of the power source **413** may be specified in order to generate the negative resistance in the power multiplying networks **403**_a_/**403**_b_. For example, to aid in determining such other frequency relationships between the frequency of variation of the parametric reactances **418** and the frequency of the power source **413**, see the topic of Mathieu's Equation in Cunningham, W. J., *Introduction to Nonlinear Analysis*, McGraw-Hill, 1958, pp. 259-280) on circuit dissipation.

As Cunningham demonstrates, growing oscillations (negative resistance) and regions of instability may occur in second order systems for certain other noninteger (i.e. not commensurable) frequency ratios, which, in the presence of damping, also depend upon system dissipation as well as the amplitude and phase of the parameter variation. These are commonly manifested as the region of instability "tongues" in the solutions of Mathieu's equation. Also, see Kharkevich, A. A., *Nonlinear and Parametric Phenomena in Radio Engineering*, John F. Ryder Publisher, Inc., 1962, pp. 166-166; Mandelshtam, L. I. and Papaleksi, N. D., "On the Parametric Excitation of Electric Oscillations," Soviet Journal of Technical Physics, Vol. 4, No. 1, 1934, pp. 5-29. See FIG. 1, p. 9.) Such other frequencies may also be employed, although efficiency may suffer at such other ratios.

The parametric reactances **418** may be implemented using any one of a number approaches. In particular, the parametric reactances **418** may be created electrically, mechanically, thermally, or via some other approach. Specific examples include the creation of a parametric inductance L(t) using a magnetic amplifier that involves varying the permeability μ of a core about which an inductor is wound. As the permeability μ is altered, so is the inductance of the winding. Also, in another example, the parametric capacitance C(t) may be created using a dielectric amplifier in which the permittivity $\in$ of a dielectric associated with the parametric capacitance C(t) is varied over time. As the permittivity $\in$ is varied, the resulting capacitance of the parametric capacitance C(t) is varied. Also, the parametric reactance may be created mechanically using wheels and the like. For a more detailed discussion as to the various devices that may be used or approaches taken to implement the parametric reactances **418**, reference is made to the following papers:

Manley, J. M. and Peterson, E., "*Negative Resistance Effects in Saturable Reactor Circuits,*" *AIEE Transactions*, Vol. 65, December 1946, pp. 870-88;

Mandelstam, L., Papalexi, N., Andronov, A., Chaikin, S., and Witt, A., "*Report on Recent Research on Nonlinear Oscillations,*" *Technical Physics of the USSR, Leningrad*, Volume 2, Number 2-3, pp 81-134, 1935;

Mumford, W. W., "Some Notes on the History of Parametric Transducers," *Proceedings of the IRE*, Vol. 48, May 1960, pp. 848-853; and

Raskin, J-P., Brown, A. R., Khuri-Yakub, B. T., Rebeiz, G. M., "A Novel Parametric-Effect MEMS Amplifier," Journal of Microelectromechanical Systems, Vol. 9, December 2000, pp. 528-537.

Each of these references is incorporated herein by reference in their entirety.

According to one embodiment, the power multipliers **400**_a_ and **400**_b_ are each described as including a power multiplying network **403**_a_/**403**_b_ comprising a multiply-connected, velocity inhibiting circuit constructed from a number of lumped-elements.

In addition, the term "lumped" is defined herein as effectively concentrated at a single location. Thus, the terms "lumped-elements" refer to discrete, two-terminal, concentrated electrical elements such as capacitance, inductances, resistance, and/or conductance. Thus, the lumped-elements as described herein may comprise discrete inductors, capacitors, or resistors. In addition, as contemplated herein, lumped-elements may also comprise diodes, transistors, and other semi-conductors that may be described, for example, as nonlinear resistors or conductors that have resistance or conductance that is controlled by the polarity of applied voltages or currents, etc. In addition, lumped-elements may also comprise inherent capacitances, inductances, resistances, or conductances of various electrical structures such as helices, parallel plates, or other structure as will be discussed. Similar to the power multiplying network **203**, the directional coupler **209** is also constructed using lumped-elements.

Lumped elements are circuit components for which the parameters inductance, capacitance, resistance, and conductance have the same meaning as in the static situation. That is to say, the first order terms in the electromagnetic power series solution of Maxwell's equations are adequate to describe "lumped element" networks. This usually occurs when the dimensions of the components, including interconnections, is very small compared to the wavelength of operation. As the ratio of network dimension to wavelength is decreased, Maxwell's rigorous field equations transition to the distributed-element transmission line equations of Heaviside, and, in the limit, these pass to the lumped element circuit equations of Kirchoff. Only the latter are necessary to describe electrical circuits operating in the lumped element regiem of conventional electronic circuit theory. No spatial integrals or spatial derivatives are necessary to analyze discrete component networks as would be required for distributed-elements and radiating circuits.

According to various embodiments, the parametric excitation as described above applies to power multipliers that comprise distributed element circuits as well. A distributed element circuit is a circuit whose reactance (inductance and/or capacitance) are distributed over a physical distance that is comparable to an operating wavelength of the circuit. Power multipliers that include a ring comprising a distributed element circuit include those that substantially are not velocity inhibiting circuits. For distributed element power multipliers, Maxwell's rigorous field equations transition to the distributed-element transmission line equations of Heaviside. A distributed element power multiplier are analyzed using spatial integrals or spatial derivatives. A distributed element power multiplier is one with a waveguide comprising a ring with a physical circumference that is an integer multiple of the wavelength λ_w of an exciting traveling wave that accumulates in the ring. It follows that for a distributed element power multiplier to be practical, the frequency of operation is relatively high, resulting a relatively small structure that can be practically constructed. In this respect, the power multiplier **100** (FIG. **1**) comprises a distributed element power multiplier.

In another embodiment, the principles of parametric excitation of a power multiplier described above with reference to the lumped-element power multipliers **400***a*/**400***b* apply equally to distributed element power multipliers. The reactance parameters of distributed ring power multipliers may be varied in space and time ("pumped") appropriately by any one of a variety of means. For example, the transmission line electrical parameters may be pumped by employing a magnetically biased plasma. They may be pumped by using a magnetically biased permeability varying in space and time, $\mu(x,t)$. Also, they may be pumped appropriately by using a voltage-controlled electrical permittivity, $\in(x,t)$, in the transmission line. Such techniques, obviously, have the effect of pumping the inductance per unit length $L(x,t)$ and the capacitance per unit length $C(x,t)$, respectively, at the desired pump frequency and phase. For one discussion of techniques for pumping reactance variations in the context of conventional distributed element parametric amplifiers, reference is made to Louisell, W. H., *Coupled Mode and Parametric Electronics*, John Wiley and Sons, Inc., 1960, pp. 131-147, and the references cited and discussed therein, which is incorporated herein by reference.

The power multipliers described (i.e. the power multipliers **400***a*/**400***b*, and other embodiments such as distributed element power multipliers) above that employ the principles of parametric excitation may be employed in the same manner as the power multipliers **200** and **250** described above. For example, the power multipliers **400***a*/**400***b* may be employed for power smoothing with respect to power distribution networks **300** as described above. Also, the power multipliers **400***a*/**400***b* (or distributed element power multipliers employing parametric excitation) may be employed in any other situation where the multiplication or storage of power is desired, where the essential difference between the power multipliers that employ parametric excitation and the power multipliers that do not is that the power multipliers that employ parametric excitation can buildup or store a vastly greater amount of power due to the fact that the physical resistance in the rings associated with such power multipliers is negated as described above.

It should be emphasized that the above-described embodiments of the present invention are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described embodiment(s) of the invention without departing substantially from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and the present invention and protected by the following claims.

Therefore, having thus described the invention, at least the following is claimed:

1. A power multiplication apparatus, comprising:

a ring power multiplier having a ring; and

a parametric reactance that negates at least a portion of a physical resistance of the ring, wherein the parametric reactance is varied by at least twice a frequency of a power signal applied to the ring power multiplier.

2. The power multiplication apparatus of claim **1**, wherein the parametric reactance comprises a parametric inductance.

3. The power multiplication apparatus of claim **2**, wherein the parametric inductance is non-linear.

4. The power multiplication apparatus of claim **2**, wherein the parametric inductance comprises a magnetic amplifier.

5. The power multiplication apparatus of claim **1**, wherein the parametric reactance comprises a parametric capacitance.

6. The power multiplication apparatus of claim **5**, wherein the parametric capacitance is non-linear.

7. The power multiplication apparatus of claim **5**, wherein the parametric capacitance comprises a dielectric amplifier.

8. The power multiplication apparatus of claim **1**, wherein the ring comprises a distributed element.

9. The power multiplication apparatus of claim **8**, wherein the parametric reactance comprises a parametric reactance-per-unit-length.

10. The power multiplication apparatus of claim **1**, wherein the ring comprises a power multiplying network having a multiply-connected, velocity inhibiting circuit constructed from a plurality of lumped-elements.

11. The power multiplication apparatus of claim **10**, wherein the parametric reactance comprises a parametric lumped-element reactance.

12. The power multiplication apparatus of claim **10**, wherein the ring power multiplier further comprises:

a launching network; and

a directional coupler coupling the launching network to the power multiplying network.

13. The power multiplication apparatus of claim **10**, further comprising a diverter coupled to the power multiplying network.

14. A method for power multiplication, comprising:

coupling AC power into a ring of a ring power multiplier;

negating at least a portion of a physical resistance of the ring by driving a parametric reactance associated with the ring; and

varying the parametric reactance by at least twice a frequency of the AC power coupled into the ring of the ring power multiplier.

15. The method of claim **14**, wherein driving the parametric reactance associated with the ring comprises driving a parametric inductance.

16. The method of claim **15**, wherein driving the parametric inductance comprises driving a non-linear parametric inductance.

17. The method of claim **15**, wherein driving the parametric inductance comprises driving a magnetic amplifier.

18. The method of claim **14**, wherein driving the parametric reactance associated with the ring comprises driving a parametric capacitance.

19. The method of claim **18**, wherein driving the parametric capacitance comprises driving a non-linear parametric capacitance.

20. The method of claim **18**, wherein driving the parametric capacitance comprises driving a dielectric amplifier.

21. The method of claim **14**, further comprising inhibiting a velocity of the AC power in the ring using a distributed element.

22. The method of claim **21**, wherein driving the parametric reactance associated with the ring comprises driving a parametric reactance-per-unit-length.

23. The method of claim **14**, further comprising inhibiting a velocity of the AC power in the ring using a power multiplying network having a multiply-connected circuit constructed from a plurality of lumped-elements.

24. The method of claim **23**, wherein driving the parametric reactance associated with the ring comprises driving a parametric lumped-element reactance.

25. The method of claim **23**, further comprising:

launching the AC power into a launching network; and coupling the AC power from the launching network into the power multiplying network using a directional coupler.

26. The method of claim **23**, further comprising diverting the AC power out of the ring to a load.

27. A system for power multiplication, comprising:

means for coupling AC power into a ring of a ring power multiplier; and

means for negating at least a portion of a physical resistance of the ring which comprises a parametric reactance that is varied by at least twice a frequency of a power signal applied to the ring power multiplier.

28. The system of claim **27**, wherein the parametric reactance comprises a parametric inductance.

29. The system of claim **27**, wherein the parametric reactance comprises a parametric capacitance.

30. The system of claim **27**, wherein the ring comprises a distributed element.

31. The system of claim **27**, wherein the ring comprises a power multiplying network having a multiply-connected, velocity inhibiting circuit constructed from a plurality of lumped-elements.

32. The system of claim **31**, wherein the parametric reactance comprises a parametric lumped-element reactance.

33. The system of claim **28**, wherein the parametric inductance comprises a non-linear parametric inductance.

34. The system of claim **29**, wherein the parametric capacitance comprises a non-linear parametric capacitance.

35. The system of claim **27**, further comprising:

means for coupling power into the ring of the ring power multiplier; and

means for diverting power out of the ring of the ring power multiplier.

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